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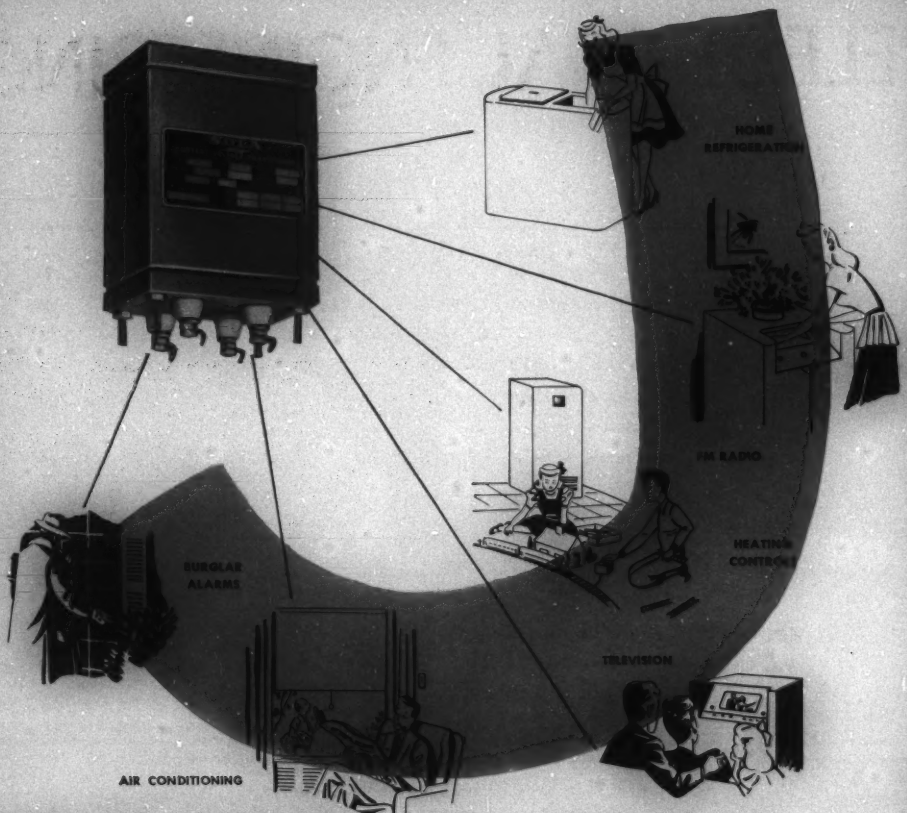

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The Cover. Necaxa hydroelectric plant in Mexico, with a static head of 1,453 feet, employs nine generators having a total capacity of 100,000 kw.

Mexican Light and Power Company, Limited, photo

Mexico's Electrification Program—II 245
Basil Nikiforoff, Alfonso F. del Busto, Alejandro Paez Urquidi, Oscar R. Enriquez

Realism in Engineering Education ..... A. S. Langsdorf ... 251

Amortisseur Action of the Squirrel Cage ..... Edward Bretch ... 255

Advances in Airport Lighting ..... W. A. Pennow ... 259

Vertical Wind Tunnel ... 265

Institute Activities ... 267

Of Current Interest ... 292

TRANSACTIONS SECTION

(Follows EE page 302; a preprint of pages 321–402 of the 1946 volume. Any discussion of these papers will appear in the June 1946 "Supplement to Electrical Engineering—Transactions Section" and in the 1946 volume.)

Speed Control Regulator ..... A. G. Conrad, F. E. Brooks, Jr., R. G. Fellers ... 321

Inductance Formulas ..... Henry Peter Messinger, Thomas James Higgins ... 328

Supervisory Control of Hydroelectric Plant ... C. W. Bohner, A. P. Maness ... 337

Signal and Noise Levels in Magnetic Tape Recording ... D. E. Wooldridge ... 343

The Mho Distance Relay ..... R. M. Hutchinson ... 353

Metal-Clad Unit-Type Switchgear for 33-Kv Service ..... C. H. Kreger ... 360

Induction Heating of Long Cylindrical Charges ..... Herbert F. Storm ... 369

Ohm and Mho Principles and Protective Relays ... A. R. van C. Warrington ... 378

Magnetic-Type Power Circuit Breakers ..... L. J. Linde, B. W. Wyman ... 386

Short-Circuit Characteristics of D-C Generators ..... G. E. Frost ... 394

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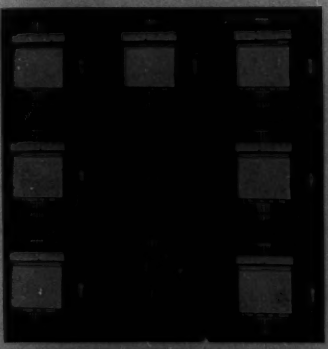

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HIGHLIGHTS.....

North Eastern District Meeting. With 439 persons registered, the North Eastern District meeting held in Buffalo, N. Y., proved to be the best attended of the spring District meetings. Of the technical sessions, those on power systems, communication and war developments, and transmission and distribution were the most popular. Much interest was evinced also in a discussion of the nontechnical problems facing the engineering profession today. This discussion was the high point of a general luncheon meeting at which questionnaires, designed to ascertain the general attitude toward a proposed reorganization of the engineering societies, were distributed. The lighter side of life was not neglected and "a good time was had by all" at the various social events included in the program (*pages 274–5*).

Southern District Meeting. A lively interest by Student members highlighted the sixth annual meeting of the Southern District, held this year in Asheville, N. C., May 14–16, with representatives from 15 of the 18 Student Branches in the District participating in the Student conference. Another highlight of the meeting was a technical program which was devoted very largely to problems of particular interest to the industrial south. Worthy of note in the general field was an address by Past President Powel describing the present condition of Germany as based upon his observations during a recent 9-month tour of that country. Mr. Powel visited Germany as a member of the Allied Control Commission (*pages 267–8*).

New Institute Policies. Expansion of the AIEE headquarters staff with a corresponding increase in its responsibilities, separation of the publication of technical papers and discussions from the publication of articles and news of general interest, and revitalization of AIEE technical activities are the objectives of new policies considered by the AIEE board of directors during the Southern District meeting (*pages 269–70*).

Airport Lighting. During the war the necessity for adequate airport lighting to insure safety of landing and take-off was realized and provided for by the United States Armed Forces. In the face of the danger entailed by an ever-increasing volume of air traffic, it is imperative that commercial airports augment the usual insufficient prewar lighting budget in order to take advantage of war-fostered developments in lighted landing aids (*pages 259–65*).

Mexican Electrification. The fulfillment of Mexico's plans for industrialization, and, in general, for raising the standard of living of the Mexican people, will depend to a large extent upon her ability to develop her as yet practically unexploited natural resources. Cognizant of this fact, the Mexican government has made provision, through legislation, for strict regulation of Mexico's growing electrical industry. These points are brought out in the second and concluding part of an article prepared by members of the Mexico Section (*pages 245–51*).

Engineering Education. Again the old question arises as to the proper ratio of cultural and technical subjects in the education of an engineer. In view of the current need to renovate technical curricula in order to keep pace with growing technological demand, Dean Langsdorf, of Washington University's schools of engineering and architecture, takes a stand on the side of an improved, more intensive technical training. Because culture cannot be acquired through a few classroom lectures, he refers that aspect of the engineer's background to the national engineering societies (*pages 251–4*).

Statistical Quality Control Conference. Reports on methods and results of statistical quality control by five speakers with experience in that field attracted a large attendance at a conference held during the recent North Eastern District meeting in Buffalo. Professor M. A. Brumbagh, University of Buffalo, acted as chairman (*page 276*).

Vertical Wind Tunnel. The new structure on Wright Field's "Hurricane Hill," an 80-foot concrete tower, houses a vertical wind tunnel in which scale models of future United States Army airplanes are tested for design defects before the actual construction stage is reached. Many of these tests, such as that for airplane spin characteristics, cannot be performed in the average wind tunnel (*pages 265–6*).

Electrical Essay. In response to the electrical essay in the April issue, solutions—a number of them correct—were received from many members. Excerpts from those offering correct solutions, as well as the complete solution given by Mr. Leeds who submitted the essay, are presented (*pages 299–300*).

Metal-Clad Switchgear. According to a paper in this issue, after 17 years of operation by the Public Service Company of Northern Illinois, 33-kv metal-clad switchgear has proved itself safe, reliable, and, in a cost comparsion with switchgear of conventional open-type construction, economical as well. At present, development of this type of equipment has been allowed to lapse but, in the interest of reduced costs, its resumption would be advantageous (*Transactions pages 360–8*).

Inductance Formulas. Formulas have been derived for calculating the inductance of single-phase coaxial busses comprised of square tubular conductors. The general formula is obtained through use of geometric mean distance theory. A simple approximate formula, the conductors being considered as indefinitely thin, is epitomized in curves which yield values sufficiently accurate for most design work (*Transactions pages 328–36*).

Induction Heating of Cylindrical Charges. A new approach is offered for the analysis of the induction heating effect by using concepts commonly applied to a-c engineering and not involving differential equations. An analysis is provided which is valid for any size of the radius of the charge and the so-called depth of penetration (*Transactions pages 369–77*).

Correction. Three minor typographical errors appearing in the paper "Applications of Thin Permalloy Tape in Wide-Band Telephone and Pulse Transformers" by A. G. Ganz which was published in the AIEE *Transactions* for April 1946, pages 177–83, are corrected herein. On the lower right-hand corner of Figure 6, page 179, 2^{-1} should be corrected to 2. In column 3, paragraph 2, line 10, page 179, α should be changed to δ. On page 182, column 2, the second equation of the appendix should read $B_{ave} = \frac{15.5ET}{NA} 10^{+9}$.

Credit Where Due. Credit was not given, as it should have been, to the Douglas Aircraft Company, El Segundo, Calif., for the illustrated chart of flight and propulsion which appeared as Figure 4 of an article entitled "Power Plants for Airplanes" published in the April 1946 issue of *Electrical Engineering*, pages 160–3.

News 267

Submission of Lamme Medal Nominations....270
Summer Convention Program....271
Annual Meeting Announcement....275
Standards....276
Section Items....277
Abstracts of Technical Papers....278
Future Meetings
AIEE....276
Other Societies....297
Personal Items....286
Membership....290
Letters to the Editor....298
New Books....302
Pamphlets....302

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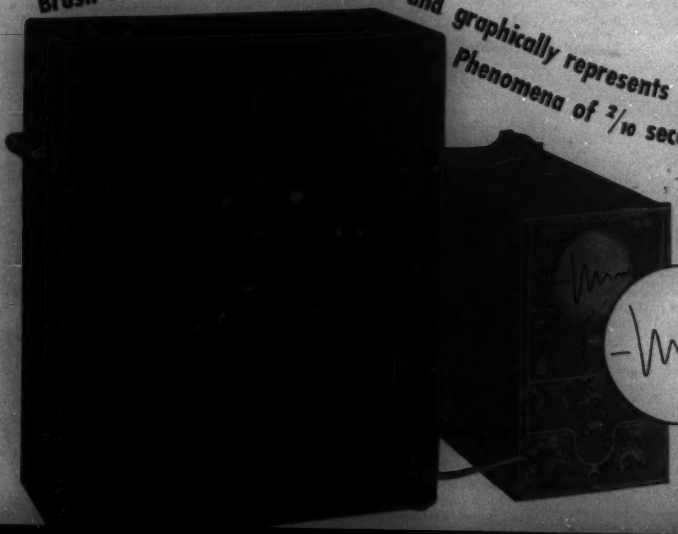

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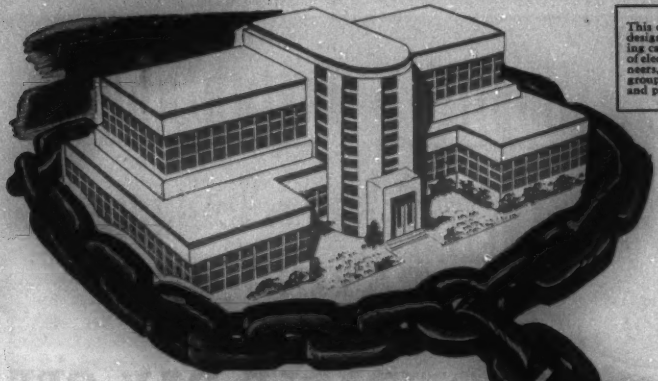

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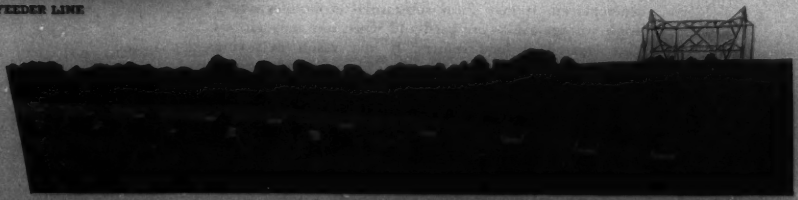

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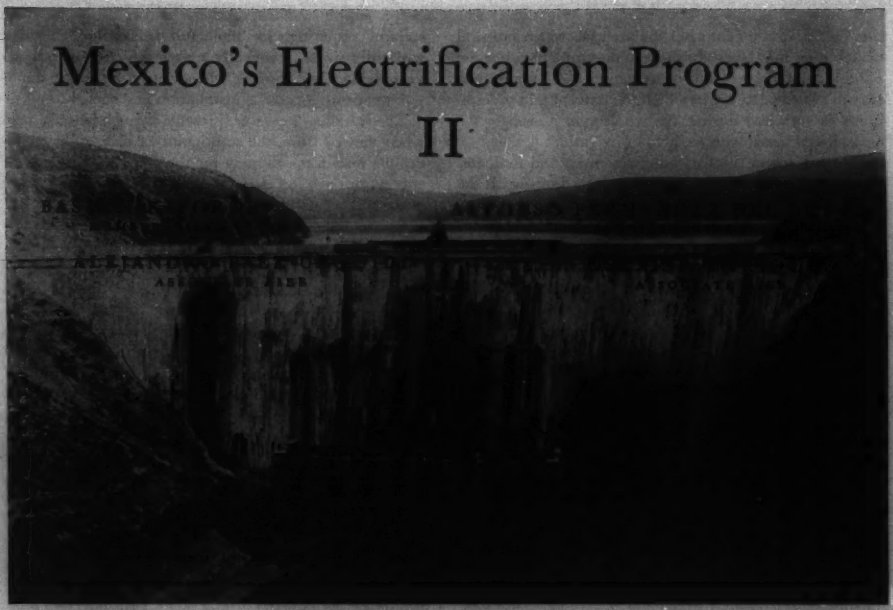
Mexico's Electrification Program
II



Continuing a discussion of Mexican electrification which began in a preceding issue, part II evaluates the country's hydraulic, oil, and coal resources and comments on possibilities for future utilization in view of increased demand. The accessibility of these resources accents their importance in Mexico's growing industrialization, a trend which is being brought about through the co-operation of government and industry. The government's role is evident in comprehensive federal legislation which regulates all activities of the electrical industry from rate fixing to the establishment of standards for electric machinery.

IF POSSIBILITIES for the utilization of atomic energy are not taken into consideration, the natural resources in Mexico which could be used for the development of motive power may be listed as follows:

1. Harnessing the natural water power of the inland waterways.
2. The use, in thermoelectric plants, of the calorific power of available coal and oil deposits.
3. Utilization of the water derived from the melting of snow and ice covering high mountain peaks.
4. The use, in certain zones of the country, of the force of the wind.

The limited scope of this article does not permit the presentation of a detailed study of the natural resources that may be utilized for the production of motive power and, consequently, in the following considerations only the data corresponding to the natural resources mentioned in the first and second categories will be treated. Also, some ideas will be expressed advocating the coordinated use of natural resources which may be advantageous for electrification in Mexico and for the development of its economy.

HYDRAULIC RESOURCES

Mexico is, comparatively speaking, a country poor in hydraulic resources. Within the territory the rainfall varies from approximately 100 millimeters average per year in the northern part of the country to somewhat more than 2,000 millimeters in the southern tropical zones. Considering the large variation in rainfall as well as the factors affecting agricultural production, Mexican territory may be classified in three distinct zones; arid, intermediate, and humid. An arid zone is one in which no

Essential substance of a paper presented by the Mexico Section at the AIEE South West District meeting, San Antonio, Tex., April 16–18, 1946. Paper was prepared under the direction of Basil Nikiforoff.

Basil Nikiforoff is chief electrical engineer and **Alfonso Fernandez del Busto** is assistant superintendent of transmission and distribution, both of the Mexican Light and Power Company, Limited, Mexico, Federal District, Mexico. **Alejandro Paez Urquidi** is head of the rate and cost department, Cia. Impulsora de Empresas Electricas, Mexico, and **Oscar R. Enriquez** is head of the hydroelectric division, Comision Nacional de Irrigacion, Mexico.

agriculture is feasible without adequate irrigation. The intermediate zone comprises the area where agricultural exploitation may be established, upon supplementing the natural rainfall by means of irrigation. A humid zone may be classified as one in which the natural rain precipitation is sufficient during the whole year to satisfy the agricultural needs without help of irrigation.

Figure 1 shows the hydraulic resources and indicates the division of Mexican territory in accordance with the classification of zones just mentioned. On the same map also is shown the division of watersheds located at different points throughout the territory as well as the regime of flow of some of the Mexican rivers. It may be observed that practically without exception the seasonal distribution of flow of these rivers is such as to require the establishment of storage reservoirs if the available water is to be used throughout the year and in an efficient way, thus necessitating the construction of dams.

In order to obtain an idea of the limitation of Mexico's hydraulic resources it may be mentioned that, at a total of 200 river-gauging and meteorological stations which have been maintained in service at the principal watersheds during a period that varies in some cases from 1890 to date, the flow registered in a total area of 530,000 square kilometers (204,600 square miles) has resulted in an average annual volume of 34,000,000,000 cubic meters (27,564,000 acre-feet). This volume corresponds approximately to that carried by the Colorado, Sacramento, and San Joaquin rivers in the United States up to the dam sites of Boulder, Shasta, and Friant, respectively.

Although the stream flow of a large number of important Mexican rivers, such as the Papaloapan, and the Uzumacinta, has not been studied properly, it has been estimated that hydraulic resources over the total extension of the country hardly reach an average annual amount of 125,000,000,000 cubic meters (approximately 100,000,000 acre-feet). The irregular orographic configuration of Mexico, with the great difference in levels between the high mountains in which the rivers originate and the Mexican Gulf and Pacific coasts where they discharge into the oceans, offers the possibility for hydroelectric developments of considerable magnitude, in spite of the comparatively low stream flow of the rivers themselves, and may be considered, in general, as favorable for such developments.

Studies made to determine the hydroelectric potentiality of Mexican streams indicate the possibility of developing approximately 6,300,000 horsepower. The water power already developed, or for which concessions have been granted, is only of the order of 800,000 horsepower, which means that only about $12^1/_2$ per cent of the hydraulic resources have been or are being developed.

It already has been mentioned that the character and distribution of population and the concentration of industries in a few localities handicaps the development of power supply systems; and the nature of the Mexican streams requiring, for their full utilization, extensive hydraulic works, frequently makes the cost of such development uneconomical when viewed from the standpoint of resulting cost of installation and energy.

The situation, however, presents a much better aspect when viewed from the standpoint of utilization of hydraulic resources, not only for the generation of electric energy, but also for purposes of irrigation and protection of the soil.

Figure 1 shows that a larger portion of Mexican territory lies in the arid zone where such combined utilization of water resources is of the greatest value, as the benefit to agriculture derived from irrigation alone justifies the high cost of such developments.

In zones with very little rainfall water constitutes the most important element for agricultural exploitation, and the supply of sufficient water for the cultivation of the fields justifies any expense and sacrifice.

This problem has been realized fully by Mexico with the resultant adoption of the present policy of irrigation works. This policy embraces the utilization of water for irrigation purposes in combination, whenever feasible, with hydroelectric generating plants. In this way it is expected to obtain maximum benefit for the economy of the country.

The utilization of the waters as described thus serves a double purpose; to encourage industrialization, and to increase agricultural production. Both purposes tend to raise the standard of living of the population and to provide the basic necessities of life. Therefore, no sacrifice or energy should be spared for the rapid development of the hydraulic resources of Mexico.

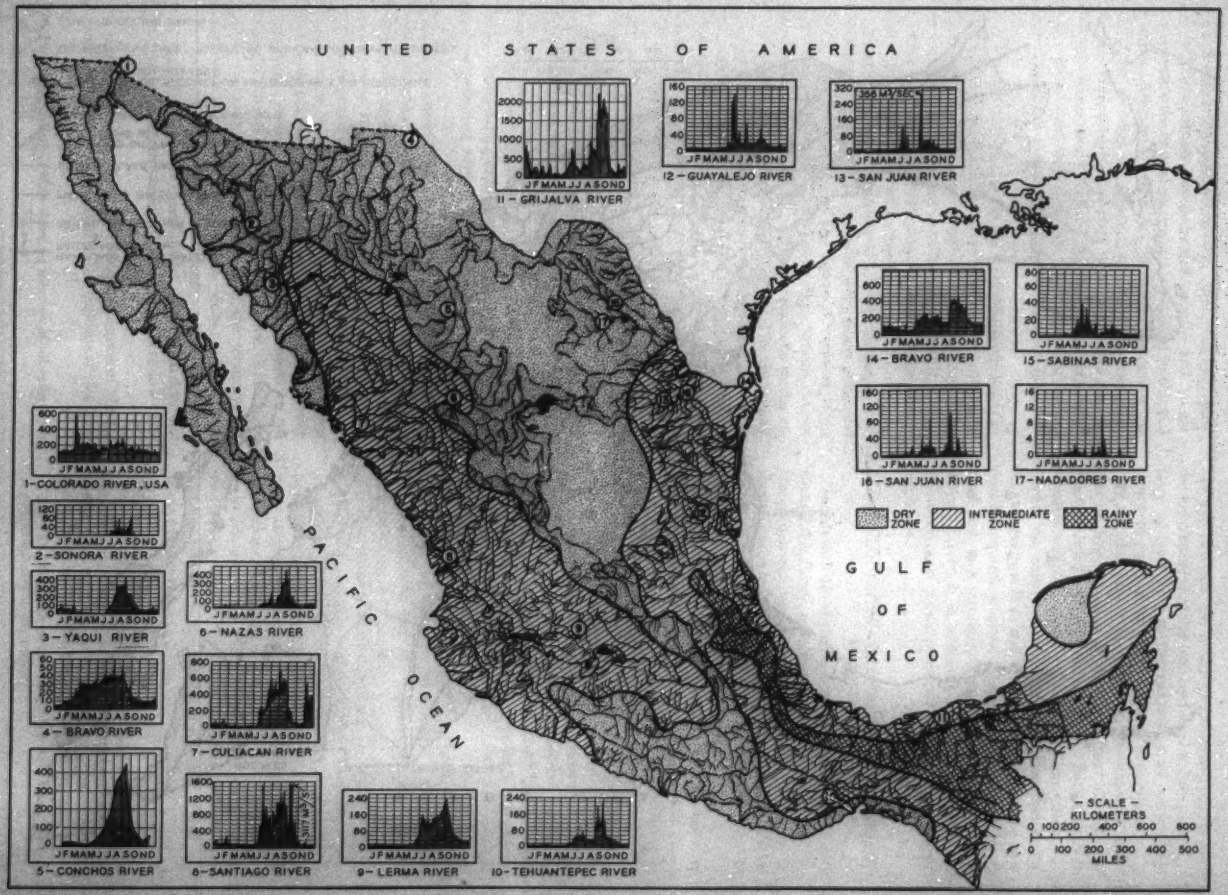
OIL RESOURCES

The Mexican Republic has been considered one of the countries with ample reserves of oil. In the opinion of geologic experts such as Wallace Pratt and Ezequiel Ordoñez, the undeveloped oil reserves of Mexico may be evaluated in something more than 24,000,000,000 barrels, and it is believed that in an area of approximately 160,000 square miles in which oil exploitation is feasible, a production totaling 27,000,000,000 barrels may be obtained. This represents approximately 75 per cent of expected oil production in the state of Texas. These amounts, if confirmed, indicate a very promising future for the exploitation of oil in Mexico.

It may be recalled that during the period from 1920 to 1922 Mexico occupied a most prominent place among oil producing countries, with an annual average produc-

Figure 1 (opposite). Map showing division of Mexico into arid, intermediate, and humid zones as well as location of watersheds

Graphs indicate representative average daily flow of various Mexican rivers (thousands of cubic meters per second)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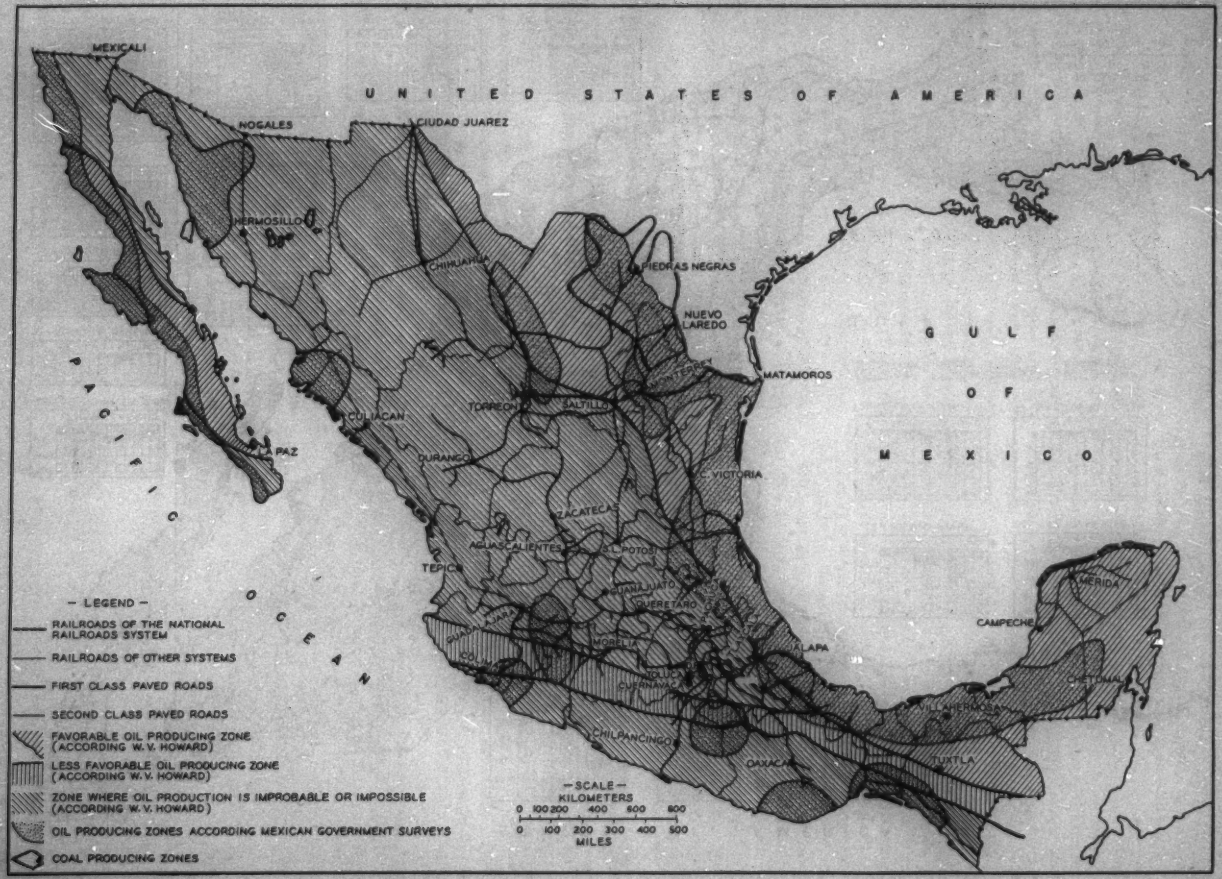
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MEXICALI
NOGALES
CIUDAD JUAREZ
HERMOSILLO
CHIHUAHUA
PIEDRAS NEGRAS
NUEVO LAREDO
MATAMOROS
GULF OF MEXICO
PACIFIC OCEAN
TORREON
SALTILLO
CULIACAN
LA PAZ
DURANGO
VICTORIA
ZACATECAS
AGUASCALIENTES
SAN LUIS POTOSI
TEPIC
GUANAJUATO
QUERETARO
MORELIA
LAPA
MERIDA
CAMPECHE
CHETUMAL
CUERNAVACA
CHILPANCINGO
OAXACA
TUXTLA
— LEGEND —
RAILROADS OF THE NATIONAL RAILROADS SYSTEM
RAILROADS OF OTHER SYSTEMS
FIRST CLASS PAVED ROADS
SECOND CLASS PAVED ROADS
FAVORABLE OIL PRODUCING ZONE (ACCORDING W. V. HOWARD)
LESS FAVORABLE OIL PRODUCING ZONE (ACCORDING W. V. HOWARD)
ZONE WHERE OIL PRODUCTION IS IMPROBABLE OR IMPOSSIBLE (ACCORDING W. V. HOWARD)
OIL PRODUCING ZONES ACCORDING MEXICAN GOVERNMENT SURVEYS
COAL PRODUCING ZONES
— SCALE —
KILOMETERS
0 100 200 400 600 800
0 100 200 300 400 500
MILES

tion of nearly 200,000,000 barrels. Since the beginning of 1924 production has decreased rapidly and at the present time the annual production is less than 50,000,000 barrels. During the last few years approximately 80 per cent of total oil production has been consumed within Mexico itself, and even if the demand for oil in Mexico is increased in the future to the extent of requiring a production of 200,000,000 barrels per year the reserves available should be sufficient for more than 100 years.

The utilization of natural gas should be given full consideration in addition to the use of oil. The volume of available gas resources has not been determined fully, although there is no doubt but that they constitute an important addition to the oil resources available for energy generation for many years to come.

Figure 2 shows the location of oil reserves throughout Mexico. The map was prepared from plans published by W. V. Howard (*Oil and Gas Journal*, December 1941) and from data obtained by actual explorations carried out by Mexican geologists. The coincidence in the results of these two studies may be noted. The abundance of these reserves suggests the possibility of using the oil for supplying energy to isolated sections of the country and for supplementing the production of hydroelectric systems as may be required for the expected demands of the growing industries.

COAL RESOURCES

The extent of Mexico's coal resources has not been defined as yet, even in the zone now being exploited. It is estimated that mineral coal reserves vary between 1.7 and 2 billion tons, with the annual production from 1890 to 1944 oscillating between 200,000 and 900,000 tons. Maximum production was 1,444,500 tons in 1925.

The principal zone of coal production in Mexico is located between the states of Coahuila and Nuevo Leon, and it is believed that this zone may extend to the state of Chihuahua although no studies have been made to determine its extent and volume. The discovery of coal resources in Mexico is of recent origin and the necessity for coal up to the present time has not been of sufficient importance to increase scientific exploration of other probable coal zones. During the past few years certain important anthracite deposits have been found in the state of Sonora and bituminous and lignite deposits are quite common in extensive zones of the territory, the potentiality of which is not known. Peat has been found in the vicinity of the city of Mexico where superficial geologic studies have been made. This fuel does not present any immediate interest due to its very low calorific power.

It may be said that even if the coal resources of Mexico have not been studied properly, the deposits of this combustible material are of sufficient importance to ensure the development of the iron and steel industries and, besides, to contribute to the production of thermoelectric power to complement hydroelectric generation.

A decisive factor in industrial development and in that of the generation of electricity from oil and coal is efficient distribution of available fuels. Such distribution requires adequate means of transportation which, in the case of oil, calls for a well-planned co-ordinated use of oil and gas pipe lines and of the railroads. In the case of coal it requires efficient transportation service by railroad and, to a certain extent, transportation over highways. Figure 2, in addition to indicating oil and coal resources, also shows principal railroads and Mexican highways.

Figure 2 (opposite). Map showing location of oil reserves in Mexico

MEXICAN LEGISLATION AND THE ELECTRICAL INDUSTRY

In Mexico all of the various activities related to the electrical industry, even those which do not involve commerce between two or more states, fall under the jurisdiction of the federal authorities and are subject to federal laws and regulations which, in turn, have their sources in the federal constitution of the country.

The generation of electric energy as well as its transformation, transmission, distribution, exportation, importation, sale, purchase, utilization, and consumption, are regulated by the Electric Industry Law of 1938 and by its regulations of 1945.

The use of federal waters or waters whose domain belongs to the nation, in the generation of electric energy, is subject to the provisions of the respective federal water laws that were in effect on the dates on which concessions were granted. New water developments are subject to the terms of the National Water Law of 1934, and its regulations of 1936.

Telegraphic, telephonic, and radio communications are subject to the Law of General Communications Facilities of 1940 and the regulations thereof issued on various subsequent dates.

Inasmuch as a detailed explanation of each one of the afore-mentioned laws and regulations would be much too lengthy to include in an article of this nature, it will be limited to a general idea of the most important dispositions contained in the Electric Industry Law and its regulations.

Article one of the Electric Industry Law gives a clear and concise idea of what the Mexican Federal Government intends to obtain through this law. The article reads as follows:

"The aims of this law are:

"I. To regulate the generation of electric energy, its transformation, transmission, distribution, exportation, importation, buying and selling, utilization and consumption, in order to obtain a better use of same for the benefit of the community.

"II. To encourage the development and betterment of the electrical industry in the country.

"III. To establish standards for the protection and safety of the life and property of persons, in matters pertaining to the electrical industry.

"IV. To fix the requirements for granting the necessary authorizations to carry out the activities related to the electrical industry.

"V. To determine which acts and omissions constitute violations to the law and to establish the corresponding penalties."

The regulatory function of the activities of the electrical industry mentioned in section one is exercised by the federal government through the Ministry of National Economy. This ministry is in charge of receiving, studying, and approving requests for concessions to carry out the activities mentioned therein, by private individuals or corporations, as well as by the state and municipal governments or by the Federal Commission of Electricity. The Ministry of National Economy is also the agency which receives, studies, and approves requests for permits to carry out the afore-mentioned activities when these activities do not involve the use of federal waters or public service activities, inasmuch as in these last two cases the law demands that said activities be subject to concessions and not just to permits.

Figure 3. "Los Morales" substation of the Mexican Light and Power Company, Limited, (20,000 kva, 85–6 kv) showing typical structure with steel-reinforced concrete poles

According to the Electric Industry Law, concessions can be granted only to Mexican individuals or to corporations organized under the Mexican laws. The duration of these concessions is for 50 years during which time the concessionaire is supposed to pay to the federal government a redemption tax equal to the value of the properties destined for public service, with exception of the value of the permanent hydraulic works. This tax payment is spread out over the 50 years of the concession at the rate of 2 per cent on the value of said properties. At the end of the 50-year period, the concessionnaire has the right to obtain a renewal of the concession for a period of time not to exceed another 50 years. During this second period the concessionnaire is not obliged to the 2 per cent payment and, on the other hand, can make annual accruals to amortize the value of the permanent hydraulic works. The money received by the federal government from the 2 per cent tax provides funds to enable the Federal Commission of Electricity to carry out its activities.

At the end of a concession, the concessionnaire may retire his installations and sell all property covered by the concession, with the exception of the permanent hydraulic works which revert to the nation without compensation. However, the federal government has the right to acquire installations and properties of the concessionnaire at the end of his concession, if it so desires, in which case the government must pay the price fixed by two experts named by both parties or by a third expert in cases of controversy.

In order to obtain a concession for activities of the electrical industry involving the use of federal waters, the solicitant previously must obtain a federal concession for the use of these waters. This concession must be requested and obtained in accordance with the requirements established by the National Water Law, the application and execution of which are in charge of the federal authorities through the Ministry of Agriculture and Development.

The rates that public service companies charge their customers for electrical service are regulated and fixed by the Ministry of National Economy through its General Electricity Bureau and Electric Tariff Commission.

The Electric Industry Law establishes the principle that electrical rates shall be fixed on the basis of allowing a fair return to the concessionnaire. The law contains rules for the determination of fair return, for the valuation of properties, and for determination of the rate of return.

The value of the properties of electrical public service concessionnaires, as represented by physical property in existence as of December 31, 1941, is determined by means of tables of unit values contained in the regulations of the law at present in effect. The investments in physical property made subsequent to December 31, 1941, are taken at cost in national currency on the date

they are made. To the value of the physical properties, determined as has been explained, should be added the value of the intangibles which in no case can exceed 15 per cent of the value of the physical property, and, in addition, an amount is added for working capital. The sum of these three elements constitutes the rate base on which the fair return is allowed.

The rate of return, according to the regulations of the Electric Industry Law, must be fixed with due consideration of the return made by other public service companies, and in general by other undertakings that are similar from the viewpoint of the risks, and of the amount and term of the investment. However, in no case should a rate of return be fixed at a lower figure than the highest rate of return corresponding to governmental bond issues, unless the concessionnaire requests and accepts a lower rate of return.

Naturally, the legislation also provides that the operating and maintenance expenses, taxes, except income tax which is not considered as an operating expense, insurance, and the retirement and replacement fund also should be taken into consideration in order to fix rates for a public service company.

Aside from the regulation exercised by the federal government on the activities of the electrical industry, there exists a control on the part of the federal authorities on installations for generation, transformation, transmission, distribution, and utilization of electric energy, from the standpoint of protection and safety to the life and property of persons. The Ministry of National Economy, through the General Electricity Bureau, watches, by means of previous approvals of plans and of inspections of installations, the proper observance of safety rules and specifications that must be fulfilled by all electrical installations according to the respective stipulations contained in the National Electric Code and subsequent rulings issued from time to time in line with new technical developments. The National Electric Code in general is modeled after that of the United States and contains the minimum safety requirements that electrical installations must fulfill.

All electric materials, devices, apparatus, or machinery used or sold in Mexico must fulfill certain essential characteristics of corresponding types approved by the Ministry of National Economy. Sales not complying with these essential specifications are subject to a fine.

The foregoing presents a general picture of the most important dispositions of the Electric Industry Law and its regulations. It is hoped that these rules will encourage the development and betterment of the electrical industry in Mexico, on the part of private industry as well as on the part of the federal government.

Realism in Engineering Education

A. S. LANGSDORF
FELLOW AIEE

Citing the cultural education of an engineer as a continuing process, Dean Langsdorf tosses the responsibility to the national engineering societies. He opposes further dilution of engineering curricula which already require streamlining and intensification if, in the face of expanding technology, they are to meet effectively their obligation of assuring their graduates the requisite fundamentals.

STANDING for the moment at the threshold of what we fondly hope may be a long era of world peace, it is appropriate to pause sufficiently to take stock of the trends that characterize our sector of the educational front, to the end that we may chart a course toward the goal we wish to reach. By definition we in education belong to a profession dedicated to the utilization of the forces and materials of nature for the benefit of mankind, and therefore it may be concluded that our objective is a peaceful world if it be granted that war is detrimental to human welfare. Somehow we must reconcile this conclusion with the fact that in the nearly 2,000 years of the Christian era there have been only 257 years of complete peace, and that in the 165 years of United States history from 1776 to 1941 the intervals between the country's major wars have averaged only slightly more than 25 years. We also must reconcile our conclusions with the fact that the art and science of engineering as it developed in civil life is a direct outgrowth of military engineering, and that in time of war such as we have experienced recently, the best scientific and tech-

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nical brains have been diverted to destructive ends. Does it not follow that the basic philosophy of engineers, and of physical scientists in general, henceforth must be so oriented as to contribute effectively to a world-wide pattern of social betterment?

ENGINEERS AND HUMAN RELATIONS

It is this consideration—that engineers and engineering are concerned with human relations, just as they obviously are concerned with impersonal forces, materials, and machines—that is the motivating idea of those educators who, within the recent past, have insisted upon a revision of engineering curricula to the end that approximately 20 per cent of the student's time be devoted to social and humanistic subjects. There can be no quarrel with the implication that engineering graduates must be something more than slide-rule pushers having no thought beyond the technicalities of their jobs; that they must be, in addition, responsible citizens willing and able to assume responsibility for the guidance of social, economic, and political affairs as these are affected by technology. But the 20 per cent dictum, when applied to the generally prevailing 4-year curriculum, means, in my opinion, that the remaining 80 per cent is grossly inadequate for a decent minimum of the basic sciences and technology. Without that minimum equipment of scientific training the graduate will cease to have the specialized mental equipment which alone entitles him to be listened to with respect on technical subjects. Insofar as this opinion is valid, it would seem to follow that there are only two alternatives: the lengthening of the curriculum to a minimum of five years, or some compulsion which will force the 4-year graduate to read and study on his own initiative after achieving a diploma. There is every reason to believe that within a relatively short time the 5-year curriculum is likely to supplant the presently prevailing 4-year arrangement. This lengthening of the course of study probably will come about eventually anyway, not because of the desirability of adding social and humanistic subjects, but because of the absolute necessity of incorporating in the training period an amount of the rapidly developing fundamental sciences that underlie their even more rapidly increasing applications sufficient to qualify the technical graduate to practice in his chosen field. More and more it will be necessary for technical schools to teach those fundamental subjects which are learned best under competent guidance, and to omit those subjects which can be mastered easily by a trained mind without special instruction and guidance. Why, for example, is it not entirely feasible to utilize the summer vacation periods for assigned reading in subjects such as general literature, history, biography, economics, or political science, in lieu of requiring a student to listen to lectures on these subjects at the rate of three, four, or five hourly doses per week? The lecture system of imparting information of this kind in any case is not so effective as independent reading. Someone once defined the lecture system as an educational device for transferring information from the notebook of the professor to the notebook of the student without the painful necessity of straining the material through the mind of either party.

THE TEACHER'S ROLE

I am convinced that the enlightenment of students concerning the social and economic aspects of modern industrial civilization can be secured as a by-product of instruction in science and technology provided the teachers of those subjects are enlightened and well-informed. This leads, of course, to the conclusion that teachers of engineering and science must be versed in the liberal arts at least as well as they want the young graduates to be. Not enough are. May it not be that some of the shortcomings of the average engineering graduate are attributable to the inadequacies of some of the teachers to whom he was exposed? There is no doubt but that the teaching profession is in great need of a larger percentage of vigorous and creative minds than it now possesses; teachers who by precept, and especially by example, have the power of stimulating the minds they presumably are molding. There is some bitter truth in George Bernard Shaw's salty mot: "Those who can, do; those who can't, teach." Part of the difficulty of securing and holding really first-class teachers is the limited income assigned to them by common consent. The monastic influence in education is still powerful; the notion that a teacher is set apart as a creature dedicated to poverty and obedience. Such circumstances are not attractive to vigorous and independent minds. Better salaries in the colleges would help to widen the field from which teachers might be recruited, and work must be done in that direction.

Tinkering with the curriculum is the great indoor sport of the educational world, and the effort to secure allocation of 20 per cent of the engineering curriculum to cultural instruction is merely the latest manifestation of what has been going on for a long time. Its ultimate objective is laudable—the desire to raise the intellectual level of the engineering profession because of widespread dissatisfaction with existing conditions. There are some who apparently believe that the inclusion of the 20 per cent of cultural subjects will of itself convert a young man of 22 or 23 into a sage capable of reforming the world by solving economic and social problems that have troubled mankind through all the ages. On the contrary, the acquisition of culture and wisdom is a life-long process. Education is not a kind of treatment that can be concentrated within school and college years; it is the end-product of a life of thoughtful study. If that fact is admitted, it must follow that the education of engineers is even more a function of the national engineering societies than it is that of the colleges. The colleges can and must serve as the preliminary training ground for the novitiates, but their subsequent mature

development must be the concern of the profession as a whole. For example, consider the case of the Association of Atomic Scientists, the men who staffed the laboratories at Clinton, at Los Alamos, and at the Metallurgical Laboratory in Chicago. They were professional physicists, chemists, and engineers who, for the most part, had not been exposed to the 80–20 per cent regime. Yet they had the wisdom and the foresight to see what disaster their work might bring upon mankind, and they took vigorous action in the interest of what they conceived to be the public welfare of the whole world. In my opinion, these scientists have set an example that all the engineering societies well may emulate; the dedication of their collective strength as a great moral force in the field of human relations.

Pedagogical Buck Passing

The College Teacher:
From stupid freshmen may I be spared,
The high schools send 'em up so unprepared.

The High School Teacher:
What results from us can you expect
When grade school teaching is so inept?

The Grade School Teacher:
If kindergarten teachers these kids would train,
They'd save us lots and lots of pain.

The Kindergarten Teacher:
Pity the homes from which these youngsters come,
Their parents must be extremely dumb.

The Mother:
Poor stupid child, you're not to blame,
Your father's folks were all the same.

Query:
Shall father in his own defense be heard?
No, let mother have the final word!

Lest these remarks would seem to indicate that I am opposed to the inclusion of a maximum amount of cultural studies in the engineering curriculum, I might add that more than 35 years ago my first act as a dean of engineering was to include in our curriculum a full year of instruction in economics. There was much objection to this requirement on the part of students who looked upon anything borrowed from the liberal-arts program as "sissy" stuff. It is amazing that even today so many high ranking technical schools are content with only one semester of economics. To my mind, the subject of economics is inseparable from a thorough understanding of the social effects of engineering. Unfortunately economics, long ago described as the dismal science, generally is not presented to college students in the stimulating manner in which it might be.

Since engineering is concerned so largely with the production of controlled energy, recent discoveries in the field of atomic physics are certain to play an important role in future engineering developments. The great plant at Hanford, Wash., on the Columbia River, even now is yielding by-product energy at the rate of nearly 1,500,000 kw which is going to waste in heating the water of the river. The time is bound to come when a method will be found to utilize that energy for industrial purposes. It even may be that the immense radioactivity incidental to the fission process may contain a promise of obtaining electric energy without the intervention of boilers, steam turbines, and generators. That is a consideration that will affect vitally many branches of engineering. It points to the conclusion that engineering education in the future must pay more attention to the new physics and the new chemistry inherent in the process. Already the term "nucleonic engineering" has been invented to forecast what lies ahead. It will provide more material for curriculum revision, but this time the emphasis undoubtedly will be placed on two or more years of graduate instruction, since there is no hope that the whole field can be compressed into the undergraduate period.

NEED FOR ANALYSIS

Since science will not remain stationary, but rather will grow in extent as time goes on, the need to include the fundamentals of expanding knowledge within a limited time is bound to force a critical examination of existing procedures. The problem faced by the teaching profession is not unlike that of a manufacturer who must increase the quantity and quality of his product without materially increasing his unit costs. Under such circumstances a wise management makes a critical job analysis in order to cut corners. That is the procedure that the educators must adopt. There is little doubt that present-day curricula contain much more than vestigial traces of ancient tradition, and that something akin to an appendectomy is necessary to remove a few accumulated appendages. Consider, for example, the customary college course in physics, which invariably begins with an elaborate treatment of statics and dynamics, moves on into the laws of heat, caroms lightly into acoustics, then advances upon optics, electricity, and magnetism. In many institutions instruction in statics and dynamics is given concurrently with, or sometimes just before, another course covering the same principles, but taught by the department of applied mechanics. Quite commonly this double exposure is followed by another in connection with machine design or framed structures. It may be that multiple exposure of this sort serves a useful purpose in the case of students who possess obtuse minds, on the principle that constant dripping will wear away a stone, but it is likewise true that much useless duplication is the result of hidebound tradition. The excision of unnecessary repetition can do much to make room for new material that now is excluded because of lack of time.

One of the underlying reasons for dissatisfaction with existing engineering training, one that explains the desire for a broader type of training, is the circumstance that practically every engineering enterprise requires the active co-operation of many workers having a great diversity of interests. The average young graduate does not comprehend fully this interdependence of people, but tends to focus his attention upon materials and machines. It is particularly regrettable that the schools pay so little attention to the all-important subject of labor relations and labor legislation. Engineers as a class are hostile to labor unions, probably because they are harassed so frequently by the jurisdictional disputes and restrictions on productivity that characterize some union activity. Nevertheless it is a fact that labor problems are here to stay, and that engineers must learn to work in a world where these problems constantly must be met and solved. Not much prophetic ability is called for to predict that all schools soon will require that all graduates must have become acquainted with the major outlines of this vitally important subject.

THE "G. I." PROBLEM

At this time technical schools throughout the country are filled to the bursting point with returning veterans who are taking advantage of the "G.I. Bill of Rights." Some curious circumstances have resulted. Whereas the average age of current seniors, mainly 4F men who were not inducted into service, is about the normal 21 or 22, the average age of the swollen freshman classes is four to five years greater. What has happened is that the Bill has oversold the capacity of the colleges by a factor of about three to one. This situation is nearly as bad in one direction as the unwise Selective Service policy was in the other. In the name of democracy it cut off a 5-year supply of the trained young men upon whom the future of industry must depend. This was not selective service at all; it was indiscriminate, unselective service. If the United States ever again is faced with the emergency of war it is to be hoped that the engineering profession will find a tongue to protest against such a policy for the good of the nation.

The present swollen registration in engineering colleges demands that steps be taken promptly to insure much more selectivity in the admission of students than heretofore has prevailed. This is a subject which for some time has been under study by Engineers Council for Professional Development, but the existing pressure is so great that something must be done quickly. In Washington University priority is being given to former students who showed satisfactory ability when last in residence. New students with no more than high school training are accepted if their rank was in the upper third; if middle third, an aptitude test must be passed; if lowest third, admission is denied. Transfer students with a year or more of college credit must have had a freshman record averaging a C grade, and if they had more than freshman credit, their average grade must have been intermediate between C and B. Coupled with these requirements for admission are regulations for remaining. Freshmen who fall below a C average will be dropped, as well as sophomores who fail to reach an average between C and B. The principle is that no poor student should be given a place at the expense of a worthier applicant. These are emergency regulations designed to keep registration within the limits set by physical facilities. It is hoped that the same basic principle can be maintained when the crest of the present flood has passed.

THE FUTURE

The future policy of engineering colleges must take into account the reform of certain deplorable conditions that characterize primary and secondary education in the United States. The teaching of grammar virtually has disappeared from grammar schools. The English subjects taught in high schools pay little or no attention to spelling, punctuation, or composition. In many of the states, a student can graduate from high school with only one year of what is called general mathematics, but which in reality is merely arithmetic that leaves the pupils with a blissful disregard of the position of decimal points. It is almost inconceivable that in an industrial nation—dependent as it is to a high degree upon engineering and science, with all which that implies as to an understanding of quantitative relations—the educationists should have acquired such a stranglehold on the public schools. Standards are lamentably low, and by a perversion of democracy the doctrine has been established that one child is as good as another, so no one is allowed to fail. The result is a generation of undisciplined minds, in which the poor ones regard themselves as well trained, and the bright ones have no incentive to excel or to realize their full potentiality. If these statements are thought unduly pessimistic, recommended collateral reading is a book by John Tildsley, former assistant superintendent with the Board of Education of the city of New York, entitled "The Mounting Waste of Secondary Education in the United States."

Now another peril to engineering education looms on the horizon in the form of indiscriminate universal military training. Common sense would lead one to believe that, since any future war is bound to be even more technological than this last one, everything possible must be done to conserve the supply of trained engineers. If there must be universal military training, let it be so arranged that bona fide students of engineering and of medicine, dentistry, physics, and chemistry are left undisturbed except during vacation periods. If there must be Reserve Officers Training Corps units in the engineering colleges, let it be so arranged that no undue amount of time shall be diverted from fundamentals to highly specialized military subjects such as marching and counter-marching and manual of arms.

Amortisseur Action of the Squirrel Cage

EDWARD BRETCH
MEMBER AIEE

IN THE STATIONARY TRANSFORMER, electric energy, in a primary circuit, is transformed into electric energy in a secondary circuit through the medium of a mutual magnetic flux. For the purpose of this discussion, this action, whereby electric energy is transformed from the primary to the secondary circuit by purely electrical means without involving mechanical energy, is termed the transformer action.

In rotating electric machines, such as motors and generators, the main function is a transformation between mechanical and electric energy. This is accomplished by the mechanical motion of the conductors of the electric circuit across a magnetic field. The driving energy in a generator, or output in a motor, is mechanical energy. In this case where the transformation is between mechanical and electric energy, the action is termed the speed action. It is evident that in the squirrel cage motor both of these actions are involved, although the speed action, or the transformation of electric energy into mechanical energy, is the most important under running conditions.

When an electric circuit encloses a magnetic circuit, the electric and the magnetic circuits are tied together by strong mutual reactions. Any change in current in the electric circuit produces a magnetic flux change and the flux change in turn produces a counter electromotive force which tends to oppose the current change. Consequently, in such an inductive combination, the current does not follow the voltage instantly. Conversely, in a magnetic circuit that threads an electric circuit, any flux change induces a current in the electric circuit and this induced current produces a counter magnetomotive force opposing any flux change so that the flux does not instantly follow the mmf.

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Single-phase motor theory is a somewhat controversial subject because two distinct single-phase motor theories, the rotary field and the cross flux theories, have prevailed for 50 years. The physical concepts of the actions taking place in the motor that are developed by these two theories are not altogether consistent with each other or with test results and so it seems that some action is in order to co-ordinate these two theories into a single one, with the elimination of the inconsistent elements of both. The proposition that the quadrature flux of the single-phase squirrel cage motor is developed by the amortisseur action of the squirrel cage is submitted as a suggestion along this line.

Through these mutual reactions between the magnetic and electric circuits each exercises a damping effect on the other. The effect on the electric circuit produced by the reaction of its induced field is termed self-induction. The corresponding effect on the field produced by the reaction of the induced currents in the closed circuits through which it threads has not been named and is referred to here as the "amortisseur action." This amortisseur action affects the flux in the magnetic circuit in exactly the same way that self-induction affects the current in the electric circuit. With a constant mmf, the magnetic flux is determined by reluctance alone. When the mmf is varying or alternating and the flux threads closed circuits, reluctance is no longer the sole factor controlling the flux. The amortisseur or inductive action of the induced currents in the closed circuits through which the flux threads affects the magnetic flux in the same way that self-induction affects the current in the electric circuit.

An amortisseur winding is a system of low resistance electric circuits enclosing the magnetic flux utilizing this stabilizing principle to oppose rapid flux changes. It operates both by the speed action and the transformer action. When the flux strength remains constant and there is a relative motion between the conductors and the flux so that the conductors cut across the flux, an emf is generated in the electric circuit by speed action and the resulting currents oppose the motion of the conductors with respect to the flux.

When there is a change of flux strength without relative motion between the conductor and the flux, the currents induced in the electric circuit by transformer action oppose and retard any flux change. Both variations of flux strength and relative motion of the flux with respect to the conductors are opposed by this amortisseur action. Flux strength variations are opposed by the transformer

action and relative motion between the conductors and the flux by the speed action. These actions may operate either singly or simultaneously.

In a rotor, the speed and transformer actions operate in space quadrature with reference to each other and consequently do not react on each other. Thus, the two actions can operate simultaneously in the same rotor without interference. As all the conductors of a squirrel cage are short-circuited completely, the squirrel cage rotor presents a short circuit across any axis. It is, in fact, a magnetic core completely enveloped by an amortisseur winding. As all the rotor flux threads it, the flux of necessity must be subjected to the influence of the amortisseur or damping action of the closed squirrel cage circuits through which it threads. The induced amortisseur currents in the squirrel cage oppose any variation of flux strength by the transformer action as well as any change of position of the flux with reference to the rotor conductors by speed action.

In the polyphase squirrel cage motor, a unidirectional rotary mmf is set up by placing symmetrically spaced windings around the field structure excited by alternating currents that correspond in time phase with the space phase of the exciting windings. If the number of phases was infinite and the exciting waves truly sinusoidal and of constant frequency, a constant unidirectional mmf, rotating at a constant speed, would be produced. Under these ideal conditions, a squirrel cage rotor at synchronism would have no emf induced in it either by the speed or transformer action and a constant rotary field would be produced without the aid of the amortisseur action of the synchronous squirrel cage.

In practice, these ideal conditions are not fulfilled, and the amortisseur action of the synchronous squirrel cage tends to oppose and dampen out the variations from the ideal. In commercial motors the number of phases usually is confined to three phase, two phase, and single or one phase. Under these conditions, there are always variations between phase bands in the mmf impressed on the rotor and the exciting waves frequently do not approximate the sine form very closely. While a unidirectional mmf is impressed on the synchronous rotor, there are cyclic variations of strength and shape. These cyclic variations are opposed and suppressed substantially by the amortisseur action of the synchronous squirrel cage.

In the polyphase motor the individual phase actions generally are assumed to combine vectorially so as to produce a constant unidirectional mmf rotating at a constant speed without reference to the amortisseur action of the synchronous squirrel cage. This is only partially true, since the shape and strength of the primary mmf impressed on the rotor varies in the shift from one phase band to the next. At synchronism, these variations between phase band shifts are opposed and damped out by the amortisseur action of the synchronous squirrel cage which results in a substantially uniform rotating field, both as to shape and strength throughout the complete cycle, irrespective of these cyclic variations of the primary impressed mmf.

In a 2-phase motor, these phase band variations of

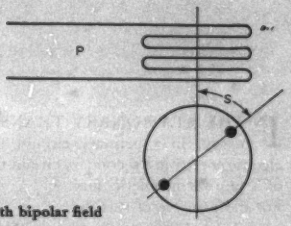

Figure 1. Rotor with bipolar field

the primary winding are quite prominent. At the instant the current in one phase is zero, the current in the other is at its crest and the total mmf is impressed by one phase alone. When the cycle has progressed 45 degrees, the mmf is impressed by both phases equally, but separated by 90 space degrees. It is evident that with the much broader combined span of both phases and the imperfections of wave form, the impressed mmfs are much different under the two conditions. These phase band mmf variations induce amortisseur currents in the synchronous squirrel cage that hold the field substantially constant throughout the cycle, both as to shape and strength even though there may be wide cyclic variations in the impressed mmf.

In a 3-phase motor, the phase band variations are less than in the 2-phase, while in the single-phase, they are at a maximum. This occurs because in the single-phase motor the impressed mmf goes through zero two times during each cycle while the synchronous squirrel cage amortisseur currents maintain the flux substantially constant during the complete cycle. As a cycle for the amortisseur currents that sustain and equalize the flux between phase bands is completed with each phase band passed by the rotor, at synchronism there is impressed on the rotor a phase band frequency six times the fundamental frequency in the 3-phase motor, four times in the 2-phase, and a double frequency in the single-phase motor.

As the phase band variations are most prominent in single-phase motors where the primary impressed mmf varies between zero and the maximum while the synchronous flux is sustained substantially constant throughout the cycle by the amortisseur action, and since the working range is limited to speeds near synchronism, the remainder of the article will be limited to the single-phase motor at and near synchronism.

Consider a bipolar field (Figure 1) with an exciting winding acting along the transformer axis across the space occupied by the rotor. The primary mmf along

this axis is proportional to the current flowing in the primary winding P. Also, consider two conductors of the squirrel cage spanning a diameter forming a rotor circuit or coil. The part of the primary mmf that is effective in this rotor circuit depends upon the sine of the space angle S it makes with the axis of magnetization. If this field is excited by a single-phase alternating current, since the current varies sinusoidally with respect to time, the mmf impressed on the field is $Ip \sin T$, where Ip represents the primary current and T the time angle of the exciting current. The mmf impressed on the secondary rotor circuit is then $Ip \sin T \sin S$.

At synchronism, $S = T$ and $\sin S = \sin T$. The synchronous mmf impressed on the rotor is $Ip \sin^2 S$, or $Ip \sin^2 T$. Mathematically, a quantity varying as the square of the sine is a quantity varying sinusoidally between zero and the positive limit at double frequency (Figure 2). The physical interpretation of this condition is not difficult. As the rotor rotates synchronously in the single-phase field, it moves from one pole to the next in the same time it takes the exciting current to reverse. Consequently it is subjected to a series of rotating unidirectional mmf impulses of double frequency varying from zero to a maximum instead of an approximately continuous unidirectional rotating mmf as in a polyphase motor. If the rotor had no closed circuits, which would eliminate any secondary mmf, the flux in the synchronous rotor would follow the impressed mmf, and vary unidirectionally between zero and the positive limit at double frequency.

This unidirectional mmf imposed on the synchronous rotor and varying sinusoidally between zero and the positive limit at double frequency can be resolved into two components (Figure 3). One of these is a positive constant component of one half the peak value of the unidirectional pulsating mmf and the other a double frequency alternating component varying between positive and negative limits of one half the peak value of the unidirectional pulsating mmf.

The effective fluxes set up by these mmf's must thread the synchronous squirrel cage. The amortisseur or choking action of the low resistance squirrel cage will oppose and choke out the double frequency flux component but will offer no opposition to the constant unidirectional component and no secondary emf will be produced by it. The extent to which the alternating component is suppressed depends upon the conductivity of the amortisseur or rotor circuit. If the rotor resistance could be reduced to zero, the alternating flux component would be eliminated entirely. While rotor resistance never can be zero, it is usually low enough so that the alternating component is eliminated substantially. This leaves a substantially constant rotor flux at synchronism.

When the squirrel cage operates at synchronism, this constant sustained rotor flux rotating at synchronism generates a counter emf in the primary winding by speed action in the same way that the rotating field of a synchronous generator does. It is a fundamental fact that a coil rotating in a constant flux generates the same emf that is produced by alternating the flux be-

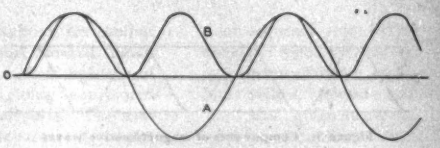

Figure 2. Magnetomotive waves

A = primary impressed mmf
B = double frequency synchronous unidirectional rotor mmf

tween the same limits at the same frequency. That is, the speed voltage and the transformer voltage are equal under like conditions. Therefore, to generate the same counter emf with the synchronous squirrel cage as with the open circuit rotor, the constant sustained rotor flux in the synchronous rotor must equal the peak single-phase flux with open circuit. Since, as is noted in Figure 3, the constant synchronous component is one half the peak impressed mmf, it follows that in order to generate the same counter emf with the synchronous squirrel cage rotor as with the open circuit rotor, the primary mmf required with the synchronous squirrel cage is double that required with the open circuit rotor. That is, the exciting current with the synchronous squirrel cage rotor producing a rotary field is double that required to produce the single-phase field with the secondary winding open-circuited.

The magnetic and electric conditions in the synchronous single-phase motor can be represented by stationary circuits as shown in Figure 4. As the alternating primary mmf is converted by synchronous rotation into a unidirectional double frequency pulsating mmf in the synchronous rotor, and this is the equivalent of a constant mmf superimposed on an alternating mmf, we may consider the excitation imposed on the synchronous rotor as produced by a direct current excitation I_e and an alternating excitation of double frequency I_a, the peak value of the alternating component being equal to the constant component. The secondary winding is separated from the primary winding by an air gap forming a magnetic circuit of relatively high reluctance. The secondary circuit in which the secondary current I_s flows is a low resistance short circuit representing the squirrel cage.

The flux due to I_e will pass through the low resistance secondary winding without opposition while that due to the double frequency component I_a will be opposed by the choking or amortisseur effect of the low resistance short-circuited secondary winding. In a transformer,

where the secondary load is entirely inductive, which is the case here, neglecting the secondary resistance, the primary current is the arithmetical sum of the exciting current plus the secondary current.

It has been shown that when circuit I_s is closed, the primary exciting current is doubled. As the exciting

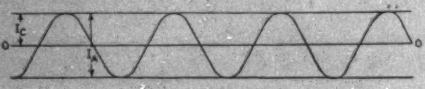

Figure 3. Components of magnetomotive waves

current is determined by open-circuit secondary conditions and the primary current is doubled by closing the secondary circuit, it follows that $I_s = 1/2 I_e$. That is, at synchronism there is a double frequency amortisseur current equal to one half the primary exciting current and also equal to the primary exciting current with open secondary winding.

While the primary exciting current and the synchronous double frequency rotor current are quite large because of the air gap in the magnetic circuit, the flux variations necessary to produce the comparatively large amortisseur currents in the rotor are not large if the secondary or rotor resistance is low. The amount of flux variation required depends on the secondary resistance.

Although the secondary resistance cannot be reduced to zero, in practice it is low enough so that the flux is held approximately constant throughout the cycle. This approximately constant flux, sustained throughout the cycle by the transformer action in the rotor and carried along with the synchronous rotor through the speed action during the interval the primary mmf is ineffective, produces a true rotary field.

The speed action of the squirrel cage rotor is understood well and need not be developed here. Each time a primary impulse is applied, or at each half cycle, the rotor flux will be pulled into synchronism and the near synchronous rotor will tend to follow it in exactly the same way as in a polyphase motor producing a torque. However, this torque is a series of double frequency impulses and drops to zero with each impulse.

It is also evident that the double frequency flux sustaining currents in the rotor that are due to the transformer action will become, as slip takes place, double frequency less slip. The slip current is due to the speed action and has a fundamental low slip frequency the same as in the polyphase motor with the impulse frequency superimposed. Thus, the resultant rotor current will comprise a low frequency slip component upon which is superimposed a double frequency component less slip.

As the speed and transformer actions operate in space quadrature in the rotor, the currents resulting from transformer action that level and sustain the flux are at a maximum 90 space degrees from the position of the maximum slip or torque currents that are due to speed action.

Such factors as reactance, resistance, slip, and iron losses prevent the sustained or cross flux from actually equalling the main flux or being displaced exactly 90 degrees, but it is not necessary to consider these factors in order to understand the fundamental principles as to how the amortisseur action operates through the transformer action to maintain the flux approximately constant throughout the cycle and through the speed action to produce a torque as the rotor tends to run in synchronism.

CONCLUSIONS

The synchronous or near synchronous squirrel cage in the single-phase motor operates as an amortisseur, opposing and suppressing sudden flux changes, either as to strength or position with relation to the rotor conductors.

The mmf impressed on the synchronous rotor is unidirectional and pulsating at double frequency between zero and a maximum.

The flux produced in the synchronous rotor by this pulsating unidirectional primary mmf is leveled off and

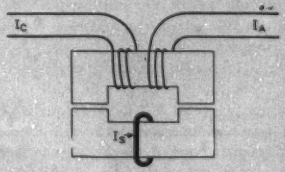

Figure 4. Representation of single-phase motor

maintained substantially constant throughout the cycle by the amortisseur action of the squirrel cage.

The induced amortisseur rotor currents, leveling and sustaining the flux constant throughout the cycle, are due to the transformer action, are of double frequency, and are equal to one half the primary exciting current. The synchronous mechanical rotation of this amortisseur sustained rotor flux produces the rotary field.

The speed action opposing relative motion between the flux and the rotor conductors, tending to pull the rotor into synchronism with the primary exciting impulses, produces a torque which pulsates at double frequency. This synchronously rotating and substantially constant rotating flux in its quadrature position is the so-called cross flux.

The speed action producing the torque and the transformer action sustaining the flux constant take place in space quadrature in the rotor and, as they do not react on each other, can operate either singly or simultaneously.

Advances in Airport Lighting

W. A. PENNOW

Developments in airport lighting for combat purposes initiated a trend toward much higher candlepower for contact lights and much more expensive lighting equipment generally for commercial airports. The new tendency is a welcome departure from the all-too-common prewar practice of allotting only one per cent or less of the airport's cost for lighted landing aids in spite of the failure of radio to provide adequate control in heavy air traffic. A combination of improved lighting with radio is offered as the only feasible method of affording the pilot the necessary margin of safety for landing or take-off.

AIRPORT LIGHTING developed for combat use differed very little basically from prewar peacetime practices, but the physical means of accomplishing those practices were, in many ways, vastly different from equipment that previously was used. As combat airports followed the flow of ground force action, equipment had to be extremely mobile; lightweight, so that it could be air-borne; simple in construction and operation, so that it could be serviced quickly and easily by semiskilled personnel; ruggedly made, so that it would stand the abuse of repeated assembly and disassembly; and most economical of electric power, as this had to come from portable air-borne gas-electric sets.

The system devised was unique in many respects. Marker and obstruction lights consisted of light stamped steel housings and plastic globes. The light used a prefocused bayonet base lamp and an automobile headlight-type socket, except that it had 120-volt insulation. The plastic globe was made in two types: symmetric and asymmetric horizontal distribution. With a clear asymmetric globe and a 40-watt T-8 bulb lamp, candlepowers over 500 were obtained in the useful zones. Mounted on a short length of fiber conduit and a stamped steel base, these were used as contact lights. Cable was supplied in 330-foot lengths and fitted with watertight push-type rubber connecting plugs. It was laid on top of the ground alongside the landing strip and the units were set on the ground and plugged together. Where a cable crossed another landing strip, it was buried two to four inches deep through the active area of the landing strip. It was possible for a three man crew and a jeep to lay both sides of a 5,000-foot runway in less than half an hour with this setup.

Asymmetric globes were supplied in clear, half clear–half yellow, and half green–half red colors. These made up a complete runway complement giving standard color sequence from either end—the pilot coming in over green, through clear, into yellow, toward red. The half green–half red units were set in lines of three or four units across the ends of the runway, green outermost. The last 1,500 feet, viewed from either end of the runway, were outlined in yellow.

Symmetric red globes were used as obstruction lights. Thirty-foot telescopic poles equipped with guy cables were standard, and could be set up easily by two men. The poles and guys could be combined for a maximum height of 60 feet, but in this case were difficult to set up with less than a four man crew, as intermediate guys carried the catenary during raising and had to be handled carefully to prevent buckling. A two man crew could set up and connect a 30-foot high obstruction light in less than ten minutes, while a four man crew could assemble, set up, and connect a 60-foot high obstruction light in about 15 minutes.

The gas-electric generator power supply was usually a 2-kva set, with a 5-horsepower 2-cylinder 2-cycle engine, with the control panel mounted as part of the set. These would handle up to 50 of the 40-watt lights, or handle one landing strip with obstruction lights and a beacon.

Additional equipment made the basic portable sets even more versatile. Small fiber cones mounted under the contact lights provided additional visibility for daytime marking. Special bases and longer lengths of fiber conduit provided an effective means of marking runways in deep snow, since the markers and cones were high enough to clear plowed banks.

Beacons were one of three types. The standard 24-inch airway beacon equipped with a special double beam lens was used in areas farthest from combat lines. A 500-millimeter Fresnel-lens-type beacon with a code flashing mechanism was used for certain operations. The most used beacon was the stroboscopic flashing type which employed the principles established by Doctor Edgerton of the Massachusetts Institute of Technology, Cambridge. This beacon consisted of a power-pack which included a step-up transformer, rectifier tubes, and capacitor bank; and a small light unit with a

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Essential substance of an address delivered at the symposium on lighting during the AIEE winter convention, New York, N. Y., January 21–25, 1946.

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Figure 1. Airport contact lights with a dead load capacity of 100,000 pounds, an improvement over 18,000-pound dead load capacity prewar models

Fresnel-type globe and a tightly wound spiral of neon tubing with special electrodes. Alternating voltage of about 1,500 volts was rectified and fed to a capacitor bank. The rate of charge was governed by a small variable resistor. As the voltage across the capacitors built up, it reached a point where the neon tube broke into ionization and the capacitors then discharged into the tube, giving a very brilliant flash of light. Using discharges of 1,000 volts and about 350 amperes, candlepowers up to 30,000,000 were obtained. The flash duration was extremely short, something less than one microsecond. The effective light was about 25,000 candlepower seconds, compared to a little over 80,000 candlepower seconds for the 24-inch beacon which has a flash duration of about 1/12 second.

The stroboscopic beacon had a continuous energy consumption of about 200 watts and light emission of about 50 watts, for an over-all efficiency, including losses in the rectifier tubes, of 25 per cent. This was unusually high for this apparatus, normal being 18 to 20 per cent. The total weight of the assembly was less than 100 pounds and it could be set up on its 25-foot telescoping tripod tower in about ten minutes by a two man crew.

Combat hoods were supplied for all portable contact, marker, and obstruction lights and the stroboscopic beacon. These were designed to limit the visible angle of the lights to a very narrow angle, about ten degrees both vertical and horizontal, so that the entire lighting system absolutely blacked out in all directions except the actual approach. This feature was of great help in the African campaign and in the South Pacific, as it permitted night operations in areas that were under rather close enemy aerial surveillance.

About 1,500 airstrips and airports in combat areas were equipped with this type of apparatus, which in some cases was moved frequently to follow the combat lines. Complete lighting for an airstrip, with lights, cable, cable reels, poles, gas-electric set, spares, packing cases, and fuel for 24 hours operation, weighed 3,600 pounds and could be carried, with the entire crew, in a DC-3-type cargo airplane. Set-up crews usually consisted of eight men and the normal time allowance for setting up a complete airstrip was two hours. It has been said that one crew in the South Pacific, having had lots of practice hopping islands, made an amazing record of complete set up in 23 minutes from the time their cargo airplane stopped rolling. This included unloading the gear, unpacking the cases, loading the equipment into motor vehicles (which were on the job), and setting all units out, that is contact lights, obstruction lights, and beacon. This may or may not be the record for set up, but it does show the extreme usefulness of this purely combat equipment.

As the bases advanced and more men and materials were carried by air, semipermanent and permanent airports were constructed to serve as supply bases. Regular types of airport lighting equipment were used, making use of the development inspired by the rough service encountered on training fields. One of these developments was the contact light, which before the war had a dead load carrying capacity of 18,000 pounds. This had to be increased to 100,000 pounds to stand up under training operations, and under service conditions involving heavy bombers and cargo airplanes. These were used on all new construction, a total of over 75,000 of these contact lights being installed in all parts of the world, enough for 700 normal sized airports.

Two new developments were made for these airports. One was a high intensity contact and approach light. This unit looked like an inverted street lighting fixture and consisted of a spun steel body, a Fresnel-type inner lens, a blown glass color screen, and an asymmetric outer globe. Sector-type reflectors were used to aid correct distribution. The unit employed a 200-watt lamp, either series or multiple, and produced a sharply controlled beam of about 35,000 maximum candlepower as compared with about 1,000 candlepower on the regular contact lights. These units, with brightness control, permitted operation under much worse weather conditions than was possible with regular equipment. About 50 airports, particularly in Alaska and the Aleutians, were equipped with these units, and their record was quite good.

The other unit was a "mobile floodlight assembly," consisting of a 15-kva 115/230-volt generator and four 3-kw landing area floodlights on a $1\frac{1}{2}$-ton truck. The generator was driven by the truck engine through a power take-off. The control arrangement, by engine governor and variable voltage, was such that frequency and voltage were held to plus or minus one per cent automatically. A switchboard permitted part or all

of the generator capacity to be diverted to outside lines for powering portable electric tools or other uses. Four 3-kva step-down transformers, 230 to 32 volts, were used, one for each floodlight.

An adjustable pedestal, mounted at the rear of the truck bed, supported the four drum-type floodlights in such manner that each floodlight was adjustable through a 30-degree arc, vertical and horizontal, and the assembly of four also could be rotated or elevated as a unit and raised from 7 feet high over-all to 12 feet. The lenses on the floodlights were one each of plain, 10-degree, 30-degree, and 80-degree spread, providing 1/4-footcandle minimum intensity on a landing strip 400 feet wide by 4,000 feet long.

One hundred and fifteen of these assemblies were built and gave excellent service on all fronts.

A companion development to the contact lights took place in the auxiliary equipment. Most notable of these was the swing from the old standard moving coil constant current regulator to the static, or monocyclic square, regulator. The principle of this regulator was known quite well but not much attention had been paid to it. As power supplies on many of these new airports were limited, the need for improved power factor on partly loaded regulators caused engineers to take another long look at the monocyclic square. Much had been learned about the behavior of the square in its application to constant voltage transformers, and by applying that knowledge to the constant current unit, a much improved combination resulted. The new regulator was much more compact and maintained power factors of 90 per cent and higher under all load conditions. Further development enabled brightness control, whereby regulator output was such that light intensity of 100, 30, 10, 3, or 1 per cent was obtained, to be built into the regulator. This was accomplished by adding taps to the output transformer on the square and using relays mounted in the regulator case. This development thus condensed the constant current regulator, brightness control transformer, five high voltage relays, and a protective circuit relay into one compact unit and raised the lowest power factor condition from less than 20 per cent to more than 90 per cent.

Another development of auxiliary equipment was the "runway selector cabinet." Previously it was necessary to use up to four high-voltage series short-circuiting relays, and four heavy-duty high-voltage series absolute cutouts, mounted on a pipe rack, to connect the regulator output to the proper runway circuit and provide protection for maintenance personnel when the lights were being serviced. Wiring of this equipment was done on the job, and the installed cost varied from $500 to $750, depending on local conditions. The space requirement was about 75 cubic feet, 5 by 5 by 3. The runway selector cabinet combined all this equipment, plus line and load terminals, in one compact unit. Installed cost was cut in half and the space requirement was reduced to nine cubic feet, 3 by 3 by 1.

Many developments of airport and airway lighting for commercial use are now under way. For airway lighting, a new high intensity obstruction light to give better identification to radio towers or other major obstructions is nearing completion. Using only one 500-watt lamp, this new unit will have a candlepower of 40,000 in red compared with less than 5,000 in red from the present marker which uses two 500-watt lamps. Instead of flashing the lamps, which often causes troublesome radio interference, the new unit has a rotating semaphore lens system under a red glass dome. A standby lamp provides a safety factor not available on present equipment.

Also nearing the final test stage is a new intermediate airway beacon for use in areas where spacings of five miles, or less, must be used, due to terrain. This new beacon has light characteristics identical with the larger airway beacons, and has a maximum candlepower of 100,000, compared to about 10,000 candlepower from the present intermediate beacon. The new beacon is enclosed completely, making it impervious to wind, rain, snow, or sleet.

In airport lighting, the most notable tendency is toward much higher candlepower on contact lights, and much more expensive equipment generally. The wails of the airport lighting engineer are being heeded at last. The common practice of building magnificent airports, then using what money is left over, if any, for lighting must be changed. There is too much at stake. The idea of limiting lighted landing aids to a cost of one per cent, or less, of the airport cost can be classed as little less than criminal negligence. As an example, an airport with a

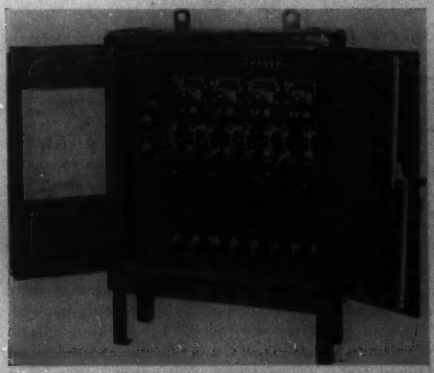


Figure 2. New runway selector cabinet which combines short-circuiting relays, series absolute cutouts, and brightness control equipment

Over-all size is approximately 3 feet by 3 feet by 1 foot

published cost of nearly $40,000,000 has field lighting equipment that costs under $100,000, or one fourth of one per cent of the total cost. Another example is an airport which costs well over $2,000,000, but the lighting equipment costs only a little over $10,000, or one half of one per cent. And these are supposedly *modern* airports.

Recently there were two airline accidents with the loss of two transport aircraft and the life of one passenger. One of these accidents occurred when a pilot tried to land the airplane during a blinding rain squall; the other

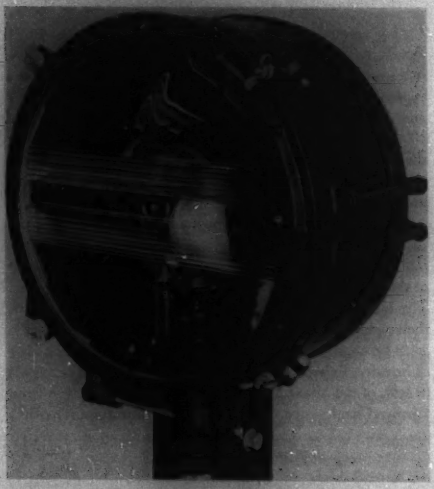


Figure 3. Projector-type approach lights which reach peaks of over one million candlepower

These lights are serviceable in daytime weather of heavy haze, or light snow or rain; or in night weather of medium fog, rain, or snow

was blamed on an attempt to land the airplane in what is described as "murky weather." Both accidents occurred at large airports on the airlines' regular schedules, and both were due to overshooting the runway.

These are not the first accidents of their kind, nor will they be the last.

Simple economics long have demanded that there must be no strings on the purse when safety is involved. These airplanes cost as much as all the lighting aids on the airports, and who will venture placing a cash value on human life? Newer, larger airplanes cost more than $1,000,000 each. One such airplane, with its load of humans, makes almost any airport lighting system seem insignificant.

But what are the engineers doing? New contact lights with candlepowers up to 100,000 are in production. These are a hundred times as powerful as those now in use.

New traffic control equipment, consisting of giant crosses and arrows made up of gaseous tube elements, have been tested thoroughly and are ready for use. These designate the runway to be used and give positive location at the end of the runway when crossed by an aircraft on an instrument approach.

Greatest engineering strides have been made on approach light systems, designed to work with so-called "blind landing" methods. Several years ago the Civil Aeronautics Administration devised the so-called "neon ladder" approach light system, which consisted of 5-foot long neon tubes in linear parabolic reflectors, mounted 100 feet apart in a row 1,500 feet long extending from the runway covered by a leg of the radio range. This system has been satisfactory in hazy daytime or light fog; or in light fog, light rain, or light snow at night; but it is useless under worse weather conditions, and is too bright on clear nights. A more recent CAA system uses projector-type equipment to supplement the ladder. These units have peaks of over 1,000,000 candlepower and are serviceable in daytime weather of quite heavy haze, light rain, or snow; and night weather of medium fog, medium rain, or medium snow.

Recently the United States Army Air Corps, the Bureau of Aeronautics of the Navy, and the Air Transport Command have been testing variations of these systems. One, called a "neon blanket," is an enlarged version of the old neon ladder. Each unit consists of 11 4-foot neon tubes. While spectacular in clear weather, it is little more effective than the neon ladder in daytime or adverse night conditions. On clear nights it is very glaring. A newer variation, with brightness control, appears much more effective.

Another unit is a variation of the projector unit, but employs an Edgerton-type flash lamp, similar to that used in the stroboscopic beacon. Sufficient data have been accumulated on this unit to prove that higher candlepower is the answer to lighting in really bad weather, and that a system with complete control of brightness is the answer to an all-weather system of approach lighting.

Such a system has been designed, and now is undergoing laboratory tests preparatory to a full scale installation. Test data at present indicate that this system will reach through any kind of weather, from clear to absolute zero-zero plus heavy snow or rain. As an indication of the power packed into this all-weather system, the candlepower range for each unit is from 100 candlepower to over *five billion*. A total of 72 units is required for each end of each runway, for a total candlepower of over 360 billion on each approach. For the first time candlepower can be talked about as glibly as is the "National Debt," with the candles at a dollar a throw.

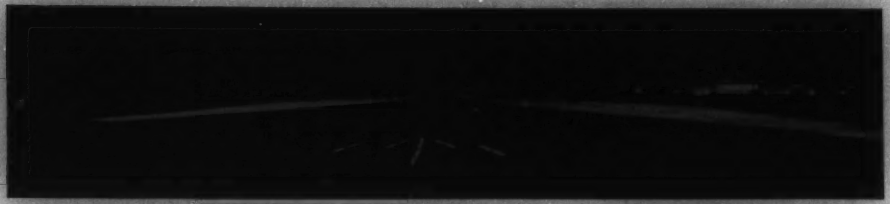


Figure 4. Giant traffic control arrows which indicate whether the runway is clear or blocked

What about costs? Staggering, when compared with past ideas of airport lighting costs. But a complete installation at each end of three runways on an airport will total less than the cost of one Lockheed Constellation! Truly, a small price for insurance against a repetition of the two recent airline tragedies.

Airport lighting for commercial use is growing up, fast! Twenty years ago, a $2,500 allocation for lighting on a million dollar airport was a lot. It has grown to a quarter million dollar allocation on a 25 million dollar airport. Perhaps the not too distant future will see an allocation of $2\frac{1}{2}$ million dollars on a 75 million dollar project. And airport lighting in this article means equipment costs, not including cable, conduit, or installation. The percentage growth up to now has been from one quarter per cent to one per cent. Three per cent appears to be an absolute minimum.

Other developments are under way for commercial and private use. One of these, now nearing the production stage, is the "approach angle indicator." It is expected that this will be a *must* supplement at all airports, regardless of size or scope. Dubbed the "missing link" by pilots who have watched it work, it unerringly indicates the correct altitude for incoming planes. It is the first piece of equipment to give elevation information that has enough candlepower to match contact light systems. The indicator projects a three-color sandwich toward the incoming plane, showing red if too low, yellow if too high, and green if at correct elevation. To avoid confusion with other lights, a mechanical shutter obscures the light for 1/2 second 40 times per minute.

On airports with contact lights, the indicator replaces contact lights located 500 feet from the end of the runway, one on each side.

On small airports it guards against overshooting or undershooting the available landing area. When used for training purposes, the time needed to teach a student good landing technique is reduced by as much as 20 per cent in some cases, as no other means teaches the feel of proper rate of descent nearly as well as this unit.

Excellent accuracy of color separation is achieved; the area of color mix, vertically, is about four feet at a mile. Two sizes of lamps are proposed: a 100-watt lamp for private airports, giving nearly 500-candlepower average across the three colors; and a 240-watt lamp for commercial airports, giving over 1,000-candlepower average. Private airports usually are not confronted with high landing speeds, and the lower candlepower is considered sufficient.

Particular emphasis is being placed on new, low cost equipment for small airports, class one and class two, by the CAA Office of Airports. New equipment soon available for these small airports includes a small double-end rotating beacon, essentially a miniature of the 36-inch airport beacon but costing about a fourth as much, and a small wind cone mounted on a 25-foot hinged pole, externally lighted and equipped with an obstruction light. Although only two thirds as long and half the

Figure 5. The approach angle indicator, sometimes referred to as the "missing link" of airport lighting

Figure 6. Small double and rotating beacon for small airports

This beacon costs only about a fourth as much as the standard 36-inch airport beacon

diameter, this cone has all the features of the standard wind cone, with an indicating range of one mile. It costs about as much with the pole as the standard wind cone itself.

Other items nearing the production stage are a new, low cost line of marker and obstruction lights, having most of the features of standard AN types, but using standard screw base lamps. There is a new low cost surface mounting contact light that bolts directly to the surface near the edge of a concrete or macadam runway. This unit has an integral junction box with watertight cable entrance bushings that projects over the edge of the runway into the earth fill. Cable is laid alongside the runway in regular trenches, breaking up to enter the contact light.

In the testing stage is a new asymmetric globe for either AN-type or the new low cost type marker lights. This will be used in place of contact lights on unpaved landing strips, on range lights, and on box lights at the ends of paved runways. This new globe also will be used on contact light extensions in snow country, giving essentially the same light distribution, and mounted on supports from 2 to 10 feet high to clear drifts or banks.

Airport lighting design engineers are busier than ever with two major problems facing them. The first, and most important, is to provide complete, all-weather lighted landing aids for commercial use to insure safety as far as possible. Do not be confused by all the loose statements that robot landings are just ahead. "Blind landing" equipment was on test in 1938; blind landings still are not made as a matter of course. Improvements in radio, loran, and radar must and will be made and they must be utilized to the fullest extent by airlines and airports. This still is not enough. Lighted landing aids must and will be used to provide that last ounce of prevention that means the difference between safe and something less than safe transportation.

The second, and most lucrative problem, is to provide complete, low cost, sturdy airport lighting equipment for small airports. This problem challenges the ingenuity of the designers in that performance and quality must be kept high while costs must be much lower than customary for this equipment. Volume production of the apparatus will not be high enough to justify the kind of tooling that brings costs down, so designs must take advantage of every bit of "know-how" and every production short cut.

As to what the future holds, there will be five general classes of airports, each with its own specific problems. The small privately owned airport, whether operated individually, by a flying club, or by a small community, either will be an all-way field having no runways or stabilized surface, or will have stabilized surface landing strips. Lighting equipment will include a small rotating beacon, a small wind cone, and either low cost boundary and obstruction lights to outline an all-way landing area, or asymmetric strip lights and approach angle indicators for stabilized surface landing strips. If activity and finances permit, a mobile lighting unit will be used as an all-purpose floodlighting system.

The small municipal airport in communities up to about 25,000 population generally will have two or three runways of stabilized soil. Lighting must be sufficient for private and feeder line aircraft, and will include a small rotating beacon, one or more small wind cones, asymmetric strip lights or low cost contact lights, obstruction lights, approach angle indicators at each end of each runway, and either a permanent floodlight system or a mobile floodlight unit.

Larger communities, up to 100,000 population, will have good sized airports with at least three paved runways, and these must be equipped to handle all types of aircraft, under some adverse weather conditions. Lighting facilities will have to be quite extensive, and should include a large rotating beacon, large wind cone or wind tee, contact lights with brightness and runway selector control, approach angle indicators, and landing area floodlights at each end of each runway, obstruction lights, and a low visibility approach lighting system consisting of neon ladder and projector approach lights at the end of at least one runway. This will be on the runway aligned with one leg of the radio range or equipped with a radio approach system.

Communities of over 100,000 population will have large airports designed primarily for commercial and feeder operations. Lighting equipment for these large airports will include a large rotating beacon, an auxiliary beacon to flash the code letters identifying the airport,

a ceiling projector for continuous check on ceiling height, a portable traffic signal for emergency control, and contact lights with brightness and selector control. At each end of each runway range lights with asymmetric globes, runway traffic control lights, approach angle indicators, landing area floodlights, a smoke wind indicator, cross and arrow runway designators, and projector-type approach lights with brightness control will be needed. Radio approach systems will be needed for one or more landing directions. Obstruction lights and taxi guidance lights also will be used.

Super airports, serving communities with over 1,000,000 population, will have at least three pairs of parallel runways, and complete all-weather lighting to insure safety of operation as far as possible.

Lighted aids for the super airport will include the large rotating beacon, auxiliary code beacon, ceiling projector, portable traffic signal, and wind cone or wind tee, or both. All runways will have high intensity contact lights with brightness control and each end of each runway will have asymmetric range lights, runway traffic control lights, landing area floodlights, cross and arrow runways designators, smoke wind indicators, and approach angle indicators. Each end of each runway normally used for landings will have an all-weather approach light system with complete intensity control. These approach lights will extend at least a half mile beyond the end of the runway.

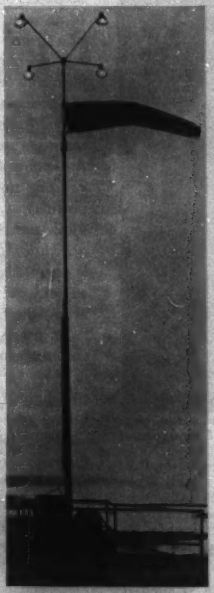


Figure 7. Illuminated wind cone for smaller airports

Taxi guidance lights will be on a block system of control, interlocked with the runway traffic control lights, cross and arrow runway designators, and approach lights so that a taxiing plane cannot be authorized to move across any runway when the runway signals indicate clear for landing or take-off. This system of control must have two stages of brightness, one for day time, the other for night use, to give adequate signals for operation 24 hours a day.

This emphasis on lighting as the major control method at airports is the result of the almost complete failure of radio control in heavy air traffic. Radio must be used to contact the incoming airplane and give preliminary approach instructions, including weather conditions, wind direction and velocity, and assigning priority for landing. Mass operations must be on a "follow-the-leader" basis, and the radio is used to set up this part of the landing operation. Once a pilot receives his weather data and is assigned his approach priority, radio contact ceases and lighting takes over. Similarly, on take-offs, radio is used to give weather and wind data, designate the runway to be used, and the taxiing route to take-off position; lighting does the rest. Thus two control officers, one on radio and the other on lights, easily can handle any volume of air traffic up to one movement per minute or more. Only by combining radio and lighting can such volume of air traffic be handled safely.

That is a picture of minimum requirements for airport lighting as it appears at present. How soon these minimum requirements will be met, particularly on large and super airports, is not apparent. Safety demands no less, and demands it now!

Vertical Wind Tunnel

WITHIN THE 80-FOOT concrete tower of the recently completed vertical wind tunnel at Wright Field, Dayton, Ohio, aerodynamic tests which may save many dollars, working hours, and even the lives of pilots now are being conducted on future Army Air Forces airplanes which are still in the blueprint stage.

The Air Matériel Command's new free-flow open-throat vertical wind tunnel, the scene of previously impossible tests for airplane spin characteristics, terminal velocity studies, parachute research, and experiments with helicopter rotor blades, has been erected near the 20-foot-wide horizontal tunnel and the 750 mile per

Based on material prepared by the public relations office of the Air Matériel Command, Wright Field, Dayton, Ohio.

Air Matériel Command photo

Figure 1. Structure housing new 80-foot vertical wind tunnel at Wright Field

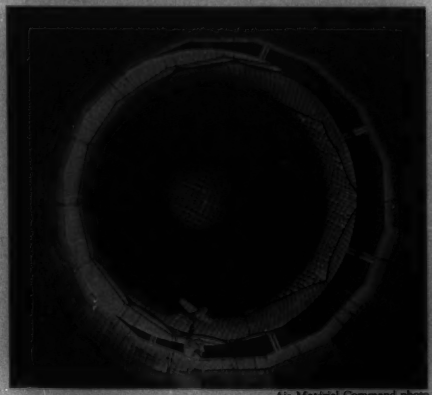
hour high-speed and high-altitude tunnel on Wright Field's "Hurricane Hill."

A 12-foot cylinder which runs up the center of the building serves as the test chamber and operational heart of the tunnel. An upward airstream is sucked through the test section and returned down an annular air passage between the inner cylinder and the outside concrete walls of the building by a 4-bladed wooden propeller, 16 feet in diameter. The fanlike propeller is turned by a 1,100-horsepower electric motor mounted above it at the top of the tunnel. Variations in airstream, ranging from almost zero to more than 100 miles per hour, are accomplished by means of a controllable pitch arrangement on the propeller, rather than by changes in the motor speed. Walls of the test section are faced with polished maple flooring to minimize airflow turbulence.

Tests are conducted from a recessed observation balcony which opens into the tunnel throat, halfway up the test section. Model airplanes, built to an extremely accurate scale from designer's specifications for new aircraft, literally are thrown from the balcony into the airflow which sweeps upward at a predetermined speed sufficient to sustain the miniature. As the model spins, dives, or climbs in the airstream, synchronized motion picture cameras located at the top and side of the test section record every motion and reaction of the plane. Subsequent study of these film records enables engineers to anticipate performance of a new ship, and to detect design errors before the full-size airplane enters the construction stage.

Wingspread on the model airplanes ranges from two to three feet, or approximately 1/30 that of a full-scale airplane. The miniatures are accurate to within 1/100 of an inch, and are balanced by weights to within 1/10 of a gram. Each free-flying model contains a complete set of controls, including ailerons, flaps, rudder, and elevators, which are operated by remote control with the precision of a pilot. The remote control mechanism, 12 half-inch solid copper cables banded together to circle the inner wall of the test chamber, magnetically activates the controls in the model airplane. As the power running through the copper rings is shut on or off, the position of the magnetized controls is changed and the flight pattern of the model is varied at the will of the operator on the observation balcony. When the test is completed the fanlike propeller is stopped, the airflow ceases, and the model falls into a nylon net stretched across the base of the test section.

As the Army continues its experimentation and development of the helicopter, the vertical tunnel will be utilized for research on rotor blades. Mounted on a streamlined hub at the base of the tunnel, model rotor blades can be tested for vibration and stress analysis while subject to simulated flight conditions created by the upsweeping airflow. Parachute models will be tested for "sway" in the airstream, and when attached from beneath to a force-recording mechanism, will be checked to determine the weight that the parachute can support safely in descent.



Air Matériel Command photo

Figure 2. Vertical wind tunnel as seen from its base

View shows, in order, polished maple surface of lower test chamber, nylon net into which models fall at completion of test, free-flying model airplane, and, at the top, vents through which a 16-foot propeller sucks winds at speeds greater than 100 miles per hour

INSTITUTE ACTIVITIES

Southern District Holds Sixth District Meeting in Asheville

With the South Carolina Section and the North Carolina Section collaborating as hosts, the sixth general conclave of the AIEE Southern District was held May 14–16 at the Grove Park Inn, Asheville, N. C. The dual features of the meeting were a very active student conference with representation from 15 of the 18 Student Branches in the District, and devotion of a large portion of the technical meetings program to the problems of especial interest to the industrial south. Total verified attendance was 373, in spite of last minute cancellation of nearly 50 advance registrations as the result of uncertainty over the railroad transportation situation. Registration statistics are given in accompanying tabulations.

The Southern District now includes 11 Sections, 4 Subsections, and 18 Student Branches. The Sections are: Alabama, East Tennessee, Florida, Georgia, Louisville, Memphis, Muscle Shoals, New Orleans, North Carolina, South Carolina, and Virginia. Subsections have become active at Little Rock, Ark., under the Memphis Section; at Charlotte, under North Carolina Section; and at Norfolk and Hampton Roads under the Virginia Section. Student Branches now are active at: Alabama Polytechnic Institute, Auburn; University of Alabama, University; Clemson Agricultural College, Clemson, S. C.; Duke University, Durham, N. C.; University of Florida, Gainesville; Georgia School of Technology, Atlanta; University of Kentucky, Lexington; Louisiana State University, Baton Rouge; University of Louisville, Louisville, Ky.; Mississippi State College, State College; North Carolina State College, Raleigh; University of South Carolina, Columbia; University of Tennessee, Knoxville; Tulane University, New Orleans, La.; Vanderbilt University, Nashville, Tenn.; Virginia Military Institute, Lexington; Virginia Polytechnic Institute, Blacksburg; University of Virginia, Charlottesville.

GENERAL SESSIONS

Presided over by AIEE Vice-President H. B. Wolf, the opening general session was given over to official welcome on behalf of the mayor of Asheville, introduction of President-Nominee J. E. Housley, and a general discussion on AIEE activities and engineering-society organization by AIEE Vice-President J. F. Fairman. Mr. Wolf called attention to the fact that the current total of 1,381 AIEE members of the Southern District represented some 22 per cent gross during the past 9 months. He paid special tribute to the individual and southern industrial organizations whose contributions enabled his student activities committee substantially to underwrite the individual cost of student participation in the District meeting and student conference.

Speaking on behalf of the mayor of Asheville, Lee M. Bauer, president of the Engineers Club of Western North Carolina, presented the city's official welcome to those in attendance at the meeting. Indicating the interest of the south in the various aspects of electrical engineering incidental to the rapidly growing industrialization, Mr. Bauer stated that in 1944 southern industry used a billion kilowatthours more than in 1941, the total representing nearly one third of all industrial power requirements of the United States. With reference to engineering activities, and especially engineering education in the south, Mr. Bauer mentioned the program of the North Carolina Engineering Foundation which, with the object of providing the men and technique necessary for southern industrial growth, is very active in a program to "give qualified young men adequate technical training at home, and then to keep them at home in the south."

Vice-President J. F. Fairman (F '35) chairman of the AIEE committee on planning and co-ordination, then discussed Institute planning and was followed by several speakers who analyzed various aspects of the committee's program in more detail (see page 268 of this issue).

"Time" was the subject of an illustrated address given to the men, women, and students of the meeting assembled at an evening session by Commodore J. F. Hellweg (retired) of the United States Naval Observatory. Commodore Hellweg briefly traced the history of mankind's continuing attempts better to determine and report accurately the passage of time. He described and pictured early crude instruments, as well as the development of more precise instruments, including his own laboratory's development of equipment which automatically puts out radiobroadcast time signals accurate to 0.001 second.

Conditions existing in Germany since her military defeat a year ago were described by Past President C. A. Powel, recently returned from a 9-month tour of duty in Germany as chief of the electrical and radio branch of the Allied Control Commission. Mr. Powel expressed great concern over the fact that the Potsdam agreement calls for the reduction of German industry to that commensurate with a domestic economy of a level of no higher than that of surrounding countries, whereas the policy recommended jointly by the presidents of the major United States engineering societies (*EE, Nov '44, pp 303–4*) recommended the reduction of German industry to a level incapable of preparing for or supporting a war of agression, but sufficient to maintain German domestic economy at something like its prewar strength with reference to its neighboring countries. Mr. Powel contended that peace would be more secure with a commercially strong German industry. Many of his listeners agreed with him, but Commodore Hellweg who is intimately familiar with the German situation, past as well as present, strongly and unqualifiedly disagreed with him.

Southern District Meeting Attendance 1928–41

Date	Location	Attendance
1946—May 14–16	Asheville, N. C.	373
1943—Nov. 16–18	Roanoke, Va.	220
1941—Dec. 3–5	New Orleans, La.	384
1938—Nov. 28–30	Miami, Fla.	282
1930—Nov. 19–22	Louisville, Ky.	300
1928—Oct. 29–31	Atlanta, Ga.	400

BUSINESS MEETINGS

The AIEE board of directors held its May meeting, a double-header session, at Asheville during the Southern District meeting, at the invitation of and by prearrangement with Vice-President Wolf and the Southern District meeting committee. Other business meetings included an evening meeting of the District 4 executive committee, and the District 4 conference on student activities, and a business meeting of the North Carolina Section.

ENTERTAINMENT

Although there were no formal social activities with the exception of a brief luncheon for the women, special features arranged by the committee provided a nicely balanced program of diversion for both men and women. The Biltmore Industries on the grounds of the Grove Park Inn, devoted to jewelry making, famous homespun clothing fabrics, and various handicrafts, proved to be almost equally attractive to both men and women. The famous 12,000-acre Vanderbilt estate, Biltmore House, adjoining Asheville drew many informal groups of visitors during the course of the meetings. The huge castle-like "house" in the French Renaissance style, completely furnished in the original manner, now is operated as a public museum. A golf tournament for men was won by D. A. Quarles (F '41) of New York, with second prize to W. J. Waicman of Charlotte, N. C.; third prize to W. T. Johns (A '44) of Richmond, Va.; and fourth prize to L. A. Coone (A '39) of Charlotte.

Analysis of Registration at Asheville

Classification	North Carolina Section	District 4*	Other Districts	Total
Members	54	77	34	165
Student members	28	65		93
Men guests	18	49	5	72
Women guests	14	19	10	43
Totals	114	210	49	373

* Outside North Carolina Section.

Among the inspection trips, the trip to the Ecusta Paper Corporation in Pisgah Forest, N. C., about 35 miles from Asheville, took first place with a registration of 110. This plant is one of the largest and one of the very few in the world specializing in the production of cigarette paper. A close second in popularity was the trip to the American Enka Corporation about 12 miles from Asheville, for which the registration exceeded 90. This huge plant is the only producer of rayon in North Carolina. A total of 55 registered for two separate trips to the 30,000-kva Glenville hydroelectric plant of the Nantahala Power and Light Company about 70 miles from Asheville. This plant enjoys the distinction of being the highest head (1,150 feet) hydroelectric plant in the East. A total of 14 registered for two trips to the Cliffside steam plant of the Duke Power Company, also about 70 miles from Asheville. Features of this plant are two 40,000-kw 3,600-rpm units operating at 900 pounds and 900 degrees; work has been started on a 65,000-kw addition to operate at 1,250 pounds and 950 degrees.

STUDENT ACTIVITIES

The following résumé of student activities at Asheville was prepared by Miss Marie Foote, senior electrical engineering student at Duke University, and one of four women engineering students in attendance at Asheville. The others were: Miss Marie Kemper of the University of Kentucky, Lexington; Miss M. Theodorsen of Duke University, and Miss Betty C. Peters of the University of Kentucky, Lexington.

The Asheville student conference reestablished the normal status of these annual meetings of the Student Branches of the Southern District. The entire District meeting program was arranged to permit Student Members to attend most of the events, including all scheduled inspection trips and still attend their own conferences. Through the co-operation and financial support of industries located throughout the Southern District, a generous portion of the expenses of each Student Member in attendance was provided for by the general committee of the District meeting.

Fifteen of the 18 Student Branches of the District were represented by students and counselors. The remaining three Student Branches are active on their campuses, but were unable to be represented at this conference, principally because of conflicting examination schedules.

Student Branches represented, together with the Student Branch representative and counselors, are as follows:

University of Alabama: John P. Hyatt, chairman; William J. Miller, counselor. Clemson Agricultural College: Thomas F. Dabney, Jr., chairman; F. T. Tingley, counselor. Duke University: Raymond M. Dunaiski, chairman; Otto Meier, Jr., counselor. University of Florida: no student delegate; E. F. Smith, counselor. Georgia School of Technology: Noel C. Turner, alternate; H. B. Dolling, counselor. University of Kentucky: James M. Hisle, chairman; Brinkley Barnett, counselor. Louisiana State University: Julian S. Johnston, Jr., chairman; A. K. Ramsey, counselor. University of Louisville: Paul F. Wantland, chairman; M. G. Northrop, counselor. North Carolina State College: J. W. Chadwick, Jr., chairman; L. M. Keever, counselor. University of South Carolina: Claude E. Walston, chairman; Samuel Litman, counselor. University of Tennessee: Robert E. Ely, Jr., chairman; J. G. Tarboux, counselor. Tulane University of Louisiana: Lester L. Lenz, chairman; M. G. Zervigon, counselor. Virginia Military Institute: John W. Trumbo, chairman; J. S. Jamison, Jr., counselor. Virginia Polytechnic Institute: Frank L. Crow, alternate; Claudius Lee, counselor. University of Virginia: Theodore T. Patterson, Jr., alternate; L. R. Quarles, counselor.

Student Branches not represented were Alabama Polytechnic Institute, Mississippi State College, and Vanderbilt University.

The Student Branch of Duke University acted as host to the student conference. Professor Otto Meier, Jr., of Duke University, presided at the student conference as chairman of the committee on student activities of the Southern District. On Tuesday, May 14, the Duke Branch sponsored an informal gathering of all students, featuring a motion picture in colors of views of the Duke campus.

On Wednesday, May 15, 6 student papers were presented at the student papers session:

"A Study of Volume Expansion," Benjamin H. Carlisle, Jr., Duke University.

"Electrical Problems in the Drainage of New Orleans," Edwin G. Hays, Tulane University.

"Units and Dimensions," J. D. Tillman, Jr., University of Tennessee.

"Wave Analysis by the Wattmeter Method," Tommy H. Landrum, University of Tennessee.

"Design and Construction of a One-Kilowatt Frequency Modulation Transmitter," James M. Hisle, University of Kentucky.

"The Engineer and the Union," Howard D. Burns, University of Alabama.

The first prize of $15 was awarded to Benjamin H. Carlisle, Jr.; second prize of $10 was awarded to J. D. Tillman, Jr.; third prize of $5 was awarded to James M. Hisle. The presentation of the student prizes was made at a general session of the District meeting by E. W. O'Brien, chairman of the AIEE committee on Student Branches. The first prize student paper by Benjamin H. Carlisle, Jr., was presented a second time before a technical session of the District meeting on Thursday, May 16.

At the business meeting of the student conference held on Thursday, May 16, it was decided that the next annual Student Branch conference of the Southern District would be held at the University of Kentucky. Professor Brinkley Barnett, counselor of the University of Kentucky Student Branch, was elected unanimously as chairman of the committee on student activities of the Southern District for 1946–47 and was designated to represent the committee at the summer convention in June 1946 at Detroit, Mich.

The student conference voted to advise the board of directors that the Student Branches of the Southern District favor the establishment of an annual lecture tour providing for lectures by nationally prominent speakers at Student Branches. The conference also recommended that *Electrical Engineering* contain a student page for the purpose of recording outstanding activities of the Student Branches.

Institute Activities Given First Place on Southern District Meeting Program

The subject of the organization of the engineering profession as a whole, as well as possible changes in AIEE procedures, which has held the limelight at both the South West and Northeastern District meetings and at many recent Section meetings, through the efforts of the AIEE committee on planning and co-ordination, again was prominent at the Southern District meeting. The subject was introduced at the opening session of the meeting at 10 a.m., Tuesday, May 14, by Vice-President J. F. Fairman (F '35) chairman of the committee.

Vice-President Fairman outlined the work that has been done to date by the AIEE committee on planning and co-ordination toward the objective of its assignment last fall of the responsibility for a general study of AIEE activities with a view toward their improvement and vitalization. Acting for T. G. LeClair (F '40), chairman of the subcommittee on professional activities, Mr. Fairman reviewed the subcommittee report as published in the April issue of *Electrical Engineering*, covering the various possible plans of organizing or reorganizing the activities of the several engineering societies. To give specific point to the several proposals, Mr. Fairman called upon D. A. Quarles (F '41) of New York to discuss the contemplated advantages of plan A covering consolidation of the engineering societies in the electrical field; C. W. Evans (M '40) of Atlanta to discuss the qualities of plan B, which contemplates the maintenance of technical activities by the present technical societies and the concentration of the so-called professional or general public questions in a separate society devoted to that particular field, such as the National Society of Professional Engineers; and P. L. Alger (F '30) of Schenectady, N. Y., to discuss

Randall Wilson

Student members and counselors in attendance at the 1946 annual Southern District Student Branch conference at Asheville, N. C., May 14–16, 1946

the qualities inherent in plan C, the plan which calls for continuance of technical activities under the existing societies, with local councils for joint action on local matters of common interest and a federation at the national level to provide facility for joint action on national and international matters of common interest. There was insufficient time to provide for any general debate on the relative merits of the different ideas, but, for the guidance of his committee, Mr. Fairman circulated and collected questionnaires.

Discussing the technical activities of the Institute, M. D. Hooven (F '44) chairman of the AIEE technical program committee and also chairman of the technical activities subcommittee of the AIEE committee on planning and co-ordination, stated that, although there was plenty of room for more initiative in the promotion and development of technical activities, it was his opinion and that of his committee, that no major changes in Institute organization are required, and that none have been discovered that would be likely to contribute materially to more efficient operation in the technical field. He reported that his committee had surveyed the activities of some 50 technical organizations for purposes of comparison and was continuing its study of AIEE technical activities. A progress report covering a résumé of the activities of the subcommittee on technical activities was published on page 222 of *Electrical Engineering* for May 1946. Mr. Hooven called attention to the fact that his technical program committee was planning to begin its work earlier in the administrative year, by planning to hold a new national convention somewhere in the Midwest in the general vicinity of Chicago in the early fall of each year. He pointed out that this additional national convention not only would provide an outlet for additional technical papers, which would relieve somewhat the growing congestion of the present summer and winter conventions, but also would get the technical program committee and the technical committees busy developing technical papers earlier in the year than has been the case with the winter convention, the first major objective of the administrative year.

Directors Take Action to Broaden AIEE Activities

Actions taken by the AIEE board of directors at its May meeting calling for expansion and vitalization of AIEE technical activities, the broadening of the publications program, the better to serve the Institute's greatly increased membership, and calling for an expansion of the headquarters staff to enable it to take a more active part in the development and leadership of AIEE activities, are hailed by informed observers as marking the opening of a new era in AIEE affairs. The board held a double-header session at Asheville during the recent Southern District meeting, to provide adequate time for the normally heavy routine business of the May meeting and to provide the equivalent of a half-day session devoted entirely to the consideration of ways and means of extending and improving AIEE activities, providing for a greater flexibility in meeting the challenges of rapid developments and changing conditions in technological and other fields of direct concern to engineers, and of more effectively serving its individual members, all matters which have been under active study by the AIEE committee on planning and co-ordination in accordance with action taken by the Board at the beginning of the current administrative year.

After a preliminary discussion of key matters had indicated the general consensus of the board, P. L. Alger, R. T. Henry, and J. R. North were appointed to act with D. A. Quarles as chairmen of a special interim committee to function at an evening session between the two meetings of the board for the purpose of preparing specific statements of policy upon which definite action could be taken. Accordingly, at its second session, the board took action as indicated in detail in the following paragraphs.

HEADQUARTERS STAFF FUNCTIONS

Heretofore, it has been traditional that the headquarters staff function essentially in a passive capacity, carrying out the office and other routine operations incidental to the AIEE program, leaving the matter of active guidance and leadership entirely in the hands of the elected officers and appointed national committees. Desirous of establishing AIEE operating policy and procedure on a basis comparable with that successfully followed in industry,

with the staff taking a more active part akin to industrial management in the leadership and co-ordination of the various elements of the organization, acting on behalf of the board of directors and in correlation with the responsible leaders of the various AIEE activity groups to carry out the policy objectives established by the board, the board voted approval of the following statement of policy with reference to headquarters staff functions: "With the rapid growth of the Institute in numbers, in technical and geographical subdivisions, and in complexity of its technical field, it is the sense of the board of directors that means should be sought to increase the effectiveness of its management and administration. As one means to this end, the board proposes to strengthen the headquarters staff as may be required to render appropriate assistance to the various committees and agencies of the Institute. To take full advantage of this, the several committees are urged to seek the counsel and assistance of the secretary of the Institute and of the members of the headquarters staff. The secretary will consider the load on the staff resulting from this policy and recommend to this board such additions or changes as he may deem necessary to meet these requirements; and all members of the headquarters staff will be impressed with their duties and responsibilities in this connection, including the need for individual initiative in offering counsel and advice and in carrying out the policies and plans established by the responsible agencies and committees of the Institute."

TECHNICAL ACTIVITIES

To provide for broadening the scope of AIEE technical activities, and to provide for an increased flexibility in the pursuit of these activities which will make possible a more prompt response to the rapid changes characteristic of many of the varied fields of electrical engineering activity, the board adopted the following resolutions:

"Resolved, that it is the sense of the board of directors that the technical activities subcommittee of the committee on planning and co-ordination should be guided by the following principles: (1) that such additional technical committees should be organized as may be needed to cover the important items of electrical technology; (2) that these technical committees should be grouped in appropriate divisions or groups with a steering committee for each group fairly compact in numbers and reasonably concentrated geographically to promote effective action; (3) that the members of the steering committees be appointed by the president, and the members of the technical committees be appointed by their respective steering committees, all to serve for one year; (4) that each year the group steering committees, in addition to appointing their several technical committees, make recommendations to the president through the secretary on the membership and organization of their respective successor committees, including at least two alternates for each chairmanship; (5) that in such recommendations the steering committees provide for a turnover of at least 25 per cent of the steering committee personnel each year. Further, that it is the intent of this board that the responsible committees should proceed with such changes as they may determine to be necessary and proper to effectuate these principles unless the proposed changes are at variance with either the constitution or the bylaws, in which event they shall be referred back to this board."

PUBLICATIONS SERVICES

Recognizing the need for expanding the publication services of the Institute commensurate with its continuing substantial growth in membership and the greatly extended scope of subject matter currently of direct interest and importance to electrical engineers, the board took action on the following specific proposal:

1. Electrical Engineering. Recommended that the monthly publication be given latitude and flexibility to function more effectively as a general service periodical, the better to meet the needs of the membership as a whole; that it be planned and operated by its editorial staff under general policies established by the board; that material from various AIEE meetings and conventions be available for editorial selection preferably from the date of original submission, but certainly from the date of presentation; that other timely material be available for editorial selection regardless of source; to be distributed monthly to all members, Student members, and subscribers.

2. Proceedings. Recommended that an intermediate series of publications, to be called "Proceedings" or by other appropriate title, be established, in several separate sections corresponding to divisions or related groups of technical activities and interests; each section to be issued every two or three months in accordance with the amount of material available and other factors involved, the several sections to be spaced around the calendar year to equalize production load; the series of periodicals to contain full text of all currently available formal technical papers together with related discussions, and in addition thereto the full text or essential substance of virtually all other material presented at AIEE conferences, District meetings, and conventions, except that otherwise published in full in *Electrical Engineering* or in special form; any one section to be available for automatic distribution without charge, upon request, to any member in addition to *Electrical Engineering*, other sections to be available upon request at cost.

3. Special Publications. Recommended that special publications be encouraged, to be issued from time to time to accommodate the publication and appropriate distribution of material of especial value and importance in its field but of limited general interest or applicability; material highly technical or mathematical in content, or specialized in subject matter such as the "AIEE Lightning Reference Book," the AIEE joint subcommittee report "Telemetering, Supervisory Control, and Associated Circuits," the "Bibliography on Automatic Stations, 1930–1941," and other bibliographies: such publications to be available to members at cost; to others at higher prices.

4. Annual Transactions. Recommended that the content of the annual *Transactions* be drawn from the entire series of AIEE meetings, programs and other appropriate AIEE sources, but be limited to material critically selected and judged on basis of most important *new* contributions, or other material specifically selected on the basis of permanent record archival value, the whole content apportioned among subject fields appropriately in accordance with membership distribution in those fields; formal discussions to be included with the papers to which they apply; decisions and selections to be made by the publication committee at the close of each calendar year on the basis of original recommendations of qualified reviewers, observed membership reactions growing out of initial presentation or publication, relative merits of the several papers in any one subject field, and other factors significant from an archival record standpoint.

5. Annual Index. Recommended that a complete composite AIEE annual index be issued appropriately covering the content of *Electrical Engineering*, *Proceedings*, *Transactions*, and special publications; to be available for appropriate distribution without charge to members, Student members, and subscribers.

With specific reference to this proposal, as outlined by Secretary Henline, the board of directors voted that: "It is the sense of the directors that the underlying plan of Institute publications be reviewed, so as to provide for a journal of general interest to the membership and separate *Transactions* and special publications which will constitute a repository of original contributions to electrical science and its application; it is further the sense of the directors that the staff should be allowed broad latitude in the accomplishment of these purposes." Secretary Henline was requested by the board to submit the foregoing suggestions and actions to the publication committee. This was done, and in all probability will result in further action by the publication committee, during the summer convention in Detroit.

1946 Year Book Issued. The 1946 edition of the AIEE Year Book has been issued, in accordance with 1945–46 budget provisions. Addresses are corrected as of November 1, 1945. Copies have been distributed to all national, District, and Section officers, Student Branch counselors, and all members of national committees. Other members may obtain copies by writing to the AIEE, 33 West 39th Street, New York 18, N. Y. The Year Book is not available to nonmembers of the AIEE; nor is its use permitted for commercial, promotional, or other circularization purposes.

AIEE Summer Convention, Detroit, Mich., June 24-28, 1946

Monday, June 24

9:30 a.m. Conference on Automatic or Supervisory Control of Air Switches

46-147—ACO.* Operating Experience With Single Pole Switching. **I. T. Knight,** Kansas City Power and Light Company

9:30 a.m. Conference on Temperature Measurements and Standards

9:30 a.m. Instruments and Measurements

46-155. Frequency Compensated A-C Ammeters and Voltmeters. **J. M. Whittenton, C. A. Wilkinson,** General Electric Company

46-133. Functional Analysis of Measurements. **I. F. Kinnard,** General Electric Company

46-135. A New Design for the A-C Network Analyzer. **J. D. Ryder, W. B. Boast,** Iowa State College

46-142. High-Vacuum Leak Testing With the Mass Spectrometer. **W. G. Worcester, E. G. Doughty,** General Electric Company

9:30 a.m. Conference on Electronics in the Electrical Engineering Curricula

9:30 a.m. Resistance Welding

46-156. Characteristics of Resistance Welding Transformers. **F. E. Murray, R. C. Jones,** The Taylor-Winfield Corporation

46-137. Influence of Magnetic Materials on the Welding Characteristics of Resistance Welding Machines. **J. J. Riley, C. E. Smith,** The Taylor Winfield Corporation

46-141. The Application of Series Capacitors to Flash Welders. **J. F. Doffenbangh,** Federal Machine and Welder Company

CP.** Voltage Change Due to Resistance Welding Loads. **C. M. Rhoades, Jr., H. A. Peterson,** General Electric Company

2:00 p.m. Conference on Section Operation and Management

There will be three separate Conferences with parallel meetings, one for the larger Sections, one for the intermediate Sections, and one for the smaller Sections. Delegates are requested to attend the meeting to which their Section is assigned.

The conference will be conducted in an informal manner. Each delegate will benefit from these conferences in direct proportion to his participation. Each meeting will be developed by discussion and questions from the floor covering the following subjects:

Operating committees
Technical groups
Fellowship
Section prize paper competition

Ten Minute Intermission

Signature of travel vouchers by delegates

Liability of Sections for injuries at meetings

Subsections

Announcement of special conferences of interest to the delegates:

(a). Local councils of engineer and technical societies

- **PAMPHLET reproductions of authors' manuscripts of the numbered papers listed in the program may be obtained as noted in the following paragraphs.**
- **ABSTRACTS of most papers appear on pages 278–86 of this issue and pages 130 of the March and 174 of the April 1946 issues.**
- **PRICES and instructions for procuring advance copies of these papers accompany the abstracts. Mail orders are advisable, particularly from out-of-town members, as an adequate supply of each paper at the meeting cannot be assured. Only numbered papers are available in pamphlet form.**
- **COUPON books in five-dollar denominations are available for those who may wish this convenient form of remittance.**
- **THE PAPERS regularly approved by the technical program committee ultimately will be published in "Transactions"; many will appear in "Electrical Engineering."**

(b). Student activities

Other activities

2:00 p.m. Conference on Section Operation and Management—Larger Sections

A. C. Muir, presiding

2:00 p.m. Conference on Section Operation and Management—Intermediate Sections

R. M. Pfalzgraff, presiding

2:00 p.m. Conference on Section Operation and Management—Smaller Sections

G. W. Bower, presiding

2:00 p.m. Conference on Automatic Switching of Capacitor Banks

46-106. Automatic Control of Large Synchronous Condensers. **M. J. Brown,** Westinghouse Electric Corporation

2:00 p.m. Conference on Electronic Instruments

The subject of the conference on electronic instruments will be limited to electronic recording instruments for potentiometric or bridge-type measurements. A short history of the development of electronic recorders will be presented. Problems encountered in perfecting the recorders and latest improvements and developments in the instruments will be discussed.

CP.** Electronically Operated Instruments for Industrial Measurements. **A. J. Horsfeck,** Bailey Meter Company

CP.** D-C to A-C Conversion Systems. **W. P. Wills,** The Brown Instrument Company

CP.** The Input Transformer Problem. **A. J. Williams, Jr.,** Leeds and Northrup Company

CP.** A New High Speed Recording Potentiometer. **V. L. Parsegian, C. J. Tagliabue** Company

CP.** Process Variables Made Available by Electronic Methods for Industrial Measurements. **D. H. Fuller,** The Foxboro Company

CP.** Sweep Balance Recorders. **George Keinath, R. K. Hellmann,** Great American Industries, Inc.

2:00 p.m. Marine Transportation and Electric Machinery

46-149. Control Problems With Diesel-Electric Synchronous Motor Ship Drives Propulsion. **E. Frisch,** Westinghouse Electric Corporation

46-127. Design of D-C Auxiliary Controllers for Marine Service. **W. Schaelchlin,** Westinghouse Electric Corporation

46-136. Current and Torque of D-C Machines on Short Circuit. **T. M. Linville,** General Electric Company

46-157. Factors Affecting Insulation Resistance of Large D-C Machines. **J. S. Johnson, C. Weil,** Westinghouse Electric Corporation

2:00 p.m. Safety

46-112. Dangerous Electric Currents. **C. F. Dalziel,** University of California

46-159—ACO.* Silent Invisible Industrial Hazard. **S. R. Warren, Jr.,** University of Pennsylvania

CP.** Shock Hazards of Low Voltage. **M. M. Brandon,** Underwriters Laboratories, Inc.; **R. L. Lloyd,** National Bureau of Standards

Tuesday, June 25

9:30 a.m. Cables

46-103. Determination of Cable Temperatures by Means of Reduced Scale Models. **Andrew Gemant, Joseph Sticher,** The Detroit Edison Company

46-115. F-3 Lead Alloy—An Improved Cable Sheathing. **L. F. Hickernell, C. J. Snyder,** Anaconda Wire and Cable Company

46-118. Semiconducting Shielding for A-C Power Cable. **E. J. Merrell,** Phelps Dodge Copper Products Corporation

46-121. High-Voltage D-C Testing of Rubber-Insulated Wire. **W. N. Eddy, W. D. Foss,** Simplex Wire and Cable Company

46-160. Moisture Equilibrium Between Gas Space and Fibrous Materials in Enclosed Electric Equipment. **J. D. Piper,** The Detroit Edison Company

9:30 a.m. Communication

46-161. System Development of Military Communications. **T. R. Putnam,** New York Telephone Company

46-162. Properties and Uses of Thermistors—Thermally Sensitive Resistors. **J. A. Becker, C. B. Green, G. L. Pearson,** Bell Telephone Laboratories, Inc.

(*Continued an next page*)

46-163. Transmission Rating of Telephone Systems. **W. A. Codd,** Stromberg-Carlson Company

46-151. Mica Capacitors for Carrier Telephone Systems. **A. J. Christopher, J. A. Kater,** Bell Telephone Laboratories, Inc.

9:30 a.m. Electric Machinery

46-164. Oscillations of a High-Voltage Secondary Winding. **A. Boyajian,** General Electric Company

46-165. Temperature Limits for Short-Time Overloads for Oil-Insulated Neutral Grounding Reactors and Transformers—Part II. **V. M. Montsinger, J. E. Clem,** General Electric Company

46-166. Some Aspects of Polyphase Motor Design—The Design and Properties of the Magnetic Circuit. **T. C. Lloyd, H. B. Stone,** Robbins and Myers, Inc.

46-116. Electromechanical Transient Performance of Induction Motors. **C. N. Weygandt, S. Charp,** University of Pennsylvania

46-167. Rotating Electric Machine Time Constants at Low Speeds. **C. Concordia,** General Electric Company

9:30 a.m. Industrial Power Applications

CP.** Progress Report on Industrial Voltage Requirements. Industrial voltage requirements subcommittee

CP.** Protective Devices in Industrial Plants. **L. C. Peterman,** Ford, Bacon and Davis, Inc.

46-122. Protection of Industrial Plants Against Insulation Breakdown and Consequential Damages. **H. R. Vaughan,** Westinghouse Electric Corporation

CP.** Modern Power Distribution Systems for Large Nonindustrial Buildings. **D. L. Beeman,** General Electric Company

2:00 p.m. Conference of Officers, Delegates, and Members

R. M. Pfalzgraff, presiding

Opening remarks by chairman

Observations on Institute Activities. **Doctor W. E. Wickenden,** president, AIEE

Opportunities for Section Activities in the Industrial Field. **J. Elmer Housley**

District and Section Activities. **H. H. Henline,** secretary, AIEE

Sections Committee Report and Forecast. **G. W. Bower,** chairman, Sections committee

Progress Report of Planning and Co-ordination Committee on the Study of Institute Activities. **J. F. Fairman,** chairman, planning and co-ordination committee

(a). Technical activities subcommittee. **M. D. Hooven,** chairman

(b). Professional activities subcommittee. **T. G. LeClair,** chairman

Ten Minute Intermission

Section Membership Activity and Its Relation to the Progress of the Institute. **L. F. Howard,** chairman, membership committee

Institute Finance and Its Relation to the Sections. **W. R. Smith,** chairman, finance committee

Reports of the First Year of Operation of the Two New Institute Sections

(a). Beaumont Section

(b). Illinois Valley Section

Educational Courses Conducted by the Sections. **H. W. Bibber,** chairman, committee on education

AIEE Publications Services. **G. Ross Henninger,** AIEE editor

Section History. **M. S. Coover,** vice-president, District 5

General Discussion

Wednesday, June 26

10:00 a.m. Annual Meeting

President W. E. Wickenden, presiding

Report of board of directors, **H. H. Henline,** secretary

Report of treasurer, **W. I. Slichter**

Reports of committee of tellers on votes for nominees for AIEE offices

Introduction of president-elect, and presentation of president's badge to **J. Elmer Housley;** response by Mr. Housley

Report on Institute prizes for papers, **M. D. Hooven,** chairman, committee on award of Institute prizes

Westinghouse centennial address, **J. K. B. Hare,** vice-president, Westinghouse Electric Corporation

Presentation of Lamme Medal to David C. Prince, vice-president, General Electric Company

Any other business that may be presented.

President's address: Doctor W. E. Wickenden

2:00 p.m. Conference on Section Activities in Connection With Local Councils of Engineering and Technical Societies

G. W. Bower, presiding

The purpose of this conference is to review the organization and operation of local councils, with particular emphasis on the part the AIEE Sections have taken in this work. The three general types of local council organizations also will be presented by selected speakers, and the activities of these councils in their local areas will be discussed. This information will be valuable in assisting Sections in expanding the activities of the councils in their local areas, and where such councils do not now exist, will assist the Sections in forming councils.

An open discussion will be featured after the presentation of each speaker.

2:00 p.m. Power Generation

46-144. Improvements in Performance of Hydroelectric Generating Units on the 2,000,000-Horsepower Saguenay System. **F. L. Lawton,** Aluminum Company of Canada, Ltd.

46-108. Tennessee Valley Authority Hydroelectric Stations—Electrical and Mechanical Design. **R. A. Hopkins, H. J. Peterson,** Tennessee Valley Authority

46-152. Modern Excitation Systems for Large Synchronous Machines. **J. B. McClure, S. I. Whittlesey, M. E. Hartman,** General Electric Company

46-154. The Development of Modern Excitation Systems for Synchronous Condensers and Generators. **F. M. Porter, J. H. Kinghorn,** American Gas and Electric Service Corporation

2:00 p.m. Relays

46-168. Low-Current Secondary Current Transformers. **An AIEE Subcommittee Report**

46-169. Protection of Powerhouse Auxiliaries. **An AIEE Committee Report**

46-109. Fault Location and Relay Performance Analyses by Automatic Oscillographs. **H. P. Dupuis, W. E. Jacobs,** The Commonwealth and Southern Corporation

46-83. Operating Experience With Distance Ground Relays. **W. A. Wolfe,** Kansas Gas and Electric Company

2:00 p.m. Conference on Arc Welding

CP.** Power Requirements for D-C Arc Welders. **R. F. Wyer, R. C. Freeman,** General Electric Company

CP.** Application of Limited Input Arc Welders to the Power Distribution System. **C. N. Clark,** Duquesne Light Company

CP.** Limited Input Arc Welders. **E. Steinart,** Westinghouse Electric Corporation

2:00 p.m. Servomechanisms

46-113. Electrical Accuracy of Selsyn Generator—Control Transformer System. **Harold Chestnut,** General Electric Company

46-114. The Frequency Response of Automatic Control Systems. **Herbert Harris, Jr.** Sperry Gyroscope Company, Inc.

46-107. Parallel Circuits in Servomechanisms. **H. T. Marcy,** Massachusetts Institute of Technology

46-150. Dimensionless Analysis Servomechanisms by Electrical Analogy. **S. W. Herwald, G. D. McCann,** Westinghouse Electric Corporation

Thursday, June 27

9:30 a.m. Protective Devices

46-134. Application Ratings of Indoor Power Circuit Breakers. **O. B. Vikoren,** Philadelphia Electric Company

46-170. Performance Criteria for Current Limiting Power Fuses—I. **C. L. Schuck,** General Electric Company

46-171. Performance Criteria for Current Limiting Power Fuses—II. **E. W. Boehne,** General Electric Company

46-172. Philosophy of Relaying. **E. W. Knapp, B. C. Hicks,** The Shawinigan Water and Power Company

46-173. Simplicity in Protective Relaying. **L. F. Hunt,** Southern California Edison Company, Ltd.

9:30 a.m. Electronic Power Conversion

46-105. Inductive Co-ordination Aspects of Rectifier Installations. **An AIEE Subcommittee Report**

Standard Report 6. Proposed Standards for Pool-Cathode Mercury-Arc Power Converters. **An AIEE Subcommittee Report**

1.000 Section. Definitions. Presentation by **H. Winograd**

2.000 Section. Standards. Presentation by **C. C. Herskind**

3.000 Section. Test Code. Presentation by **J. H. Cox**

4.000 Section. Recommended Practice and Operating Guide. Presentation by **R. C. Marcum**

5.000 Section. Rectifier Transformers. Presentation by **E. V. DeBlieux**

Discussion of "Proposed Standards Pool-Cathode Mercury-Arc Power Converter." **I. R. Smith** representing the subcommittee on metallic rectifiers, **D. E. Marshall** representing the Institute of Radio Engineers. Discussion by other groups or individuals will be welcomed.

9:30 a.m. Industrial Control Devices

46-130. Dynamic Braking Control of D-C Series Motors—Calculation of Stability Limit. **G. W. Heumann, W. P. Smith,** General Electric Company

Detroit, Mich., June 24–28, 1946 (continued)

46-104. Silicone-Resin-Treated Magnet Coils. **G. L. Moses**, Westinghouse Electric Corporation; **J. J. Torok**, Corning Glass Works

46-126. Fundamental Properties of the Vacuum Switch. **R. Keller**, University of California

46-125. An Electronic Drive for Windup Reels. **K. P. Puchlowski**, Westinghouse Electric Corporation

9:30 a.m. Basic Sciences

46-110. The Influence of the Concentration and Mobility of Ions on Dielectric Loss of Insulating Oils. **B. P. Kang, E. I. duPont de Nemours and Company**

46-120. Negative Resistance Effects in Saturable Reactor Circuits. **J. M. Manley, E. Peterson**, Bell Telephone Laboratories, Inc.

46-128. A New Approach to Probability Problems in Electrical Engineering. **H. A. Adler**, Commonwealth Edison Company; **K. W. Miller**, Armour Research Foundation

46-119. Formulas for Calculating the Inductance of Channels Located Back to Back. **W. G. Schwantz**, Commonwealth Edison Company; **T. J. Higgins**, Illinois Institute of Technology

46-111. A Fractional Termination for Ladder Networks. **W. R. LePage**, Stromberg Carlson Company. Presentation by title

9:30 a.m. Industrial Power Applications

46-153. Low-Reactance Flexible Cable for Induction Heating. **Myron Zucker**, Mackwirth G. Rees, Inc.

46-124. Design of Induction-Heating Coils for Cylindrical Magnetic Loads. **J. T. Vaughan, J. W. Williamsen**, The Ohio Crankshaft Company

46-132. Electronic Register Control for Multicolor Printing. **W. D. Cockrell**, General Electric Company

CP.** Applications in the Rubber Industry. **J. Z. Linsenmayer**, Westinghouse Electric Corporation

10:00 a.m. Conference on Student Activities

E. W. O'Brien, presiding

This conference will deal with Student Branch problems, particularly as related to the postwar problems in connection with the resumption of normal activity by the Branches.

2:00 p.m. Conference on Section–Branch Co-operation

A joint activity of the committee on Student Branches and the Sections committee

Professor V. P. Hessler, presiding

Opening remarks by the chairman

Basic Opportunities of Section–Branch Co-operation. **E. W. O'Brien**, chairman, committee on Student Branches

The Plan of Section–Branch Co-operation. **G. W. Bower**, chairman, Sections committee

Presentation by selected speakers of typical examples of Section–Branch co-operation

A Look Into the Future As a Result of Section–Branch Co-operation. **Everett S. Lee**, chairman, Engineers Council for Professional Development

An open discussion after each presentation will be a feature of this conference

In addition to the Section delegates, chairmen of the District committees on Student activities, counselors, Student Branch officers, and all other members interested in student activities are invited to attend and participate in the discussion

Friday, June 28

9:30 a.m. Power Transmission

46-175. Co-ordination of Insulation and Spacing of Transmission-Line Conductors. **W. W. Lewis**, General Electric Company

46-117. The Electrical Performance of Ceramic Dielectrics at Elevated Temperatures. **H. A. Frey, J. A. Jesatko**, Locke Insulator Corporation

46-123. The Preservative Treatment of Various Species Proposed for Poles and Crossarms. **J. D. MacLean**, Forest Service, United States Department of Agriculture

46-174. Carrier Supervisory Control of Pumping Station Over Power Cable. **W. A. Derr, W. A. Keller**, Westinghouse Electric Corporation; **H. A. W. Hedke**, United States Sugar Corporation

46-176. Six-Years' Experience With Factory-Built Unit Type Substations. **E. F. Miller, R. B. Miller**, Iowa–Illinois Gas and Electric Company

9:30 a.m. Electronic Tubes and Basic Circuits

46-139. Rectifier Capacity. **C. C. Herskind, H. C. Steiner**, General Electric Company

46-143. Nonlinear Commutating Reactors for Rectifiers. **A. Schmidt, Jr.**, General Electric Company

46-146. Circuit Cushioning of Gas-Filled Grid-Control Rectifiers. **D. V. Edwards, K. K. Smith**, Electrons, Inc.

46-138. Excitation, Control, and Cooling of Ignitron Tubes. **C. C. Herskind, E. J. Remscheid**, General Electric Company

46-140. A 400-Ampere Sealed Ignitron. **H. C. Steiner, H. N. Price**, General Electric Company

9:30 a.m. Air Transportation

46-131. Investigation of Porcelain Insulators at High Altitudes. **C. V. Fields, C. L. Cadwell**, Westinghouse Electric Corporation

46-145. Short-Time Current Ratings for Aircraft Wire and Cable. **B. W. Jones, J. A. Scott**, General Electric Company

46-148. A Unique Engine Synchronism Indicator for Aircraft. **D. B. Pearson**, General Electric Company

46-129. Electronic Control of Frequency Converter Sets for Testing Aircraft Models. **G. W. Heumann, W. F. Strong**, General Electric Company

46-85. Electric Equipment for Cornell Variable-Density Wind Tunnel. **C. C. Clymer, M. A. deFerranti**, General Electric Company. Presentation by title

46-87. Radiotelemetering for Testing Aircraft in Flight. **C. L. Frederick**, Cornell Aeronautical Laboratory. Presentation by title

9:30 a.m. Conference on Management and Quality Control

This conference is sponsored by the subcommittee on applications of statistical methods of the Standards committee. Several papers will be presented dealing with plant organization for quality control and methods of presenting results to management. Several outstanding executives also will discuss quality control from the point of view of management.

CP.** Statistical Quality Control—A Tool of Management. **T. D. Foy**, General Electric Company

*ACO: Advance copies only available; not intended for publication in *Transactions*.

**CP: Conference paper; no advance copies are available; not intended for publication in *Transactions*

Interior view of the Edison Museum, Detroit, Mich., showing locomotive exhibit

Power Systems and Communications Chief Drawing Cards at Buffalo Meeting

As might have been expected from that populous District, the three-day meeting of the North Eastern District held at the Hotel Statler, in Buffalo, N. Y., April 24–26, 1946, developed into the best-attended of the spring District meetings. However, the total registration of 439 was by no means the highest attained at a North Eastern meeting, as is evident from the table comparing registrations of former years.

Nine technical sessions, including a student session, important luncheon and committee meetings, a banquet, preceded by a social hour, and a smoker were held. Alternative inspection trips were taken to nearby industries, including a visit to the Westinghouse Motor Works or the Cornell Wind Tunnel and the hot strip mill of the Bethlehem Steel Company, where "flying shear" takes place. Another trip was to the C. R. Huntley Steam Generating Station and the Bell Aircraft Plant at Niagara Falls Airport, where several members were taken up in a helicopter. A principal event for the women who attended the meeting was a trip to Niagara Falls, which included visits to scenic spots along the frontier and a social hour and dinner, after which the illumination of the falls was viewed.

TECHNICAL SESSIONS

Most popular among the nine technical sessions were those on power systems, communication and war developments, and transmission and distribution, in the order named. Attendance at the opening session on power systems reached 200. The service record of a 1,000-kva mobile substation, electrical–mechanical features of the Jennison steam station, southeast emergency and power pooling in 1941, and automatic control of large synchronous condensers were the subjects of papers presented and discussed. R. T. Henry (F '33) vice-president of the North Eastern District, and W. S. Hill (M '35) chairman of the technical program committee presided.

A technical session on aircraft naturally aroused a great deal of interest in Buffalo, the home of several large aircraft manufacturers. The session was opened by presiding officer, D. R. Shoults (M '42) vice-president of sales, the Bell Aircraft Corporation, who introduced the first speaker, Doctor C. C. Furness, director of the Cornell Aeronautical Laboratory. Doctor Furness briefly outlined the organization and objectives of the laboratory which came into being January 1, 1946, with the gift by the Curtiss-Wright Corporation of the physical facilities of its airplane division research laboratory at Buffalo to Cornell University. Generous contributions to a working capital fund which assures the sound and continuing operation of the laboratory also were received from the Aviation Corporation, Bell Aircraft Corporation, Fairchild Engine and Airplane Corporation, Grumman Aircraft Engineering Corporation, Ranger Aircraft Engine Corporation, Republic Aviation Corporation, and the United Aircraft Corporation.

The Cornell Graduate School of Aeronautics regards the laboratory as the training ground for its advanced students in research and specialized instruction, Doctor Furness said. He explained that a realistic approach to airplane research requires a relatively large organization. "Not only must there be research and development on the airplane and its functioning as a whole," according to Doctor Furness, "but there must be continuing parallel work on the individual components, materials, and auxiliary devices. The research and development work of the Cornell laboratory is carried on by eight departments. Five of these: aerodynamics, structures, flight research, materials, and physics are the research division. The other three departments: development engineering, armament, and manufacturing constitute the development division. Thus the facilities and programs are such that a project can be carried from the basic research phase, through the stage of the first working prototype in the research division, and then on through the pilot-manufacturing stage in the development division shop. The results of the laboratory's research are to be made generally available to the public except where national security demands secrecy for some Government projects. Similarly, projects which are being supported directly by a company or groups of companies are kept confidential.

After Doctor Furness' address, papers were presented which described the electric equipment of the wind tunnel, the modern six-component wind tunnel balance system, and radio telemetering for testing aircraft in flight. The last paper presented dealt with dive testing aircraft by radio control. By courtesy of the Bell Aircraft Corporation a restricted colored motion picture of the equipment and flight of a jet-propelled plane directed by robot control for testing was shown. The telemetering equipment was designed by Princeton University and the National Defense Research Council.

Other sessions were held during the meeting on the subjects of transmission and distribution, electronics, industrial applications, aircraft and transportation, lighting, quality control, and communication and war developments. In the latter session a radar demonstration was given by E. F. Herzog of the General Electric Company.

GENERAL LUNCHEON

Nontechnical problems facing not only the AIEE but other engineering societies were the focal point of the general luncheon meeting held at noon on Thursday with R. T. Henry presiding. The question of whether the engineering profession is now organized to respond quickly to either technical or social changes was raised. Evidence that many engineering men are groping for an integrating force which will promote professional unity among the 90 engineering societies and 200,000 members was presented, and it was noted that the National Labor Relations Act likewise has introduced new problems, particularly as they affect the younger members of the profession. The degree of leadership which the AIEE should exercise in technical fields represented another debatable question.

The recent work of the AIEE committee on planning and co-ordination which is concerned with these problems was summarized by W. S. Hill, representing the committee. In his presentation of the subject Mr. Hill called attention to the greatly expanded operations of the AIEE with their accompanying new problems, and it was evident that reanalysis of the over-all operations is desirable in view of the changing character of industrial operations since the early days of the Institute. Mr. Hill outlined the technical activities subcommittee work which had been done under M. D. Hooven (F '44) and advanced the committee's proposals for improving the technical presentations, for obtaining wider publication of technical data, and for improving technical committee work. Reprints of the professional activities subcommittee's report (*EE, Apr '46, pp 169–73*) were distributed as well as a questionnaire on the four plans contained therein. Those at the luncheon were requested to give the problem careful study and return them to the committee. Representatives of many local Sections throughout the District and of adjacent Districts who were present were urged to initiate local discussions of the problem and were given additional copies of the report and questionnaire for distribution.

President W. E. Wickenden, in giving his

North Eastern District Meeting Attendance 1936–46

Date	Location	Attendance
1946—Apr. 24–26	Buffalo, N. Y.	439
1944—Apr. 19–20	Boston, Mass.	630
1943—Apr. 8–9	Pittsfield, Mass.	319
1942—Apr. 29–May 1	Schenectady, N. Y.	481
1941—Apr. 30–May 2	Rochester, N. Y.	355
1939—May 3–5	Springfield, Mass.	439
1938—May 18–20	Lenox, Mass.	417
1937—May 5–7	Buffalo, N. Y.	352
1936—May 6–8	New Haven, Conn.	310

Analysis of Registration at Buffalo

Classification	Niagara Frontier Section	District 1*	Other Districts	Totals
Members	98	113	82	293
Student Members	1	9	6	16
Men guests	58	39	17	114
Women guests	7	4	5	16
Totals	164	165	110	439

* Outside Buffalo.

views, remarked upon the interest in engineering circles which had been awakened through the activities of the planning and co-ordination committee and similar individual efforts in the other societies. He expressed the belief that there is real vigor behind this general movement and that the participation in it by engineers in other branches of the profession indicates equal interest. Because engineers generally have a collective capacity for moulding an important portion of the economic order, he is of the opinion that engineers, chemists, metallurgists, and other professional men ought to recognize their social responsibility and become a powerful collective influence in the professional and intellectual life of the country.

He spoke of the most successful technical work which the AIEE has done and is continuing to do, and the success of the AIEE in creating fellowship among engineers. He looked with concern on the increasing fragmentation occurring in all engineering societies and on the disordered confusion which frequently is apparent when the profession as a whole tries to express its views on professional matters.

Doctor Wickenden also mentioned briefly the work of the Engineers Joint Council which has taken a definite stand on several matters of national interest, particularly with reference to future military security and the demilitarization of German and Japanese industry.

DISTRICT EXECUTIVE COMMITTEE LUNCHEON

Reports of Branch and Section activity were made to the District executive committee luncheon at noon on Monday, and preliminary plans for next spring's meeting in Worcester, Mass., and for holding a summer convention in the District, possibly in 1950, were formulated. R. T. Henry presided at the luncheon.

The Ithaca Section has devised a plan for holding meetings successively in three centers of membership, Ithaca, Elmira, and Binghamton. The Niagara Frontier Section in co-operation with the Toronto Section has successfully promoted Subsection meetings with attendance from both the United States and Canada. Courses in electronics at a fee of $5 to members and $10 to nonmembers also have been offered by this Section. The Boston Section reported a negative response to its efforts to establish a Subsection in that part of New Hampshire falling within its jurisdiction. The New Hampshire members preferred the advantages of meetings in Boston. Of the 14 Student Branches in the District 14 are holding regular meetings, and all but one are organized to resume activity.

After some discussion of the subject it was agreed that local membership was both necessary and desirable in order to serve men of every caliber with interests in AIEE, and also to assist the financial program. Several Sections declared that this was a prime source for national members. The plan followed by the Boston Section is to limit local membership to three years, after which a man either must become a national member or must enter the Engineering Society of New England as a member-at-large.

The Massachusetts Sections have been reminding their members that the "grandfather clause" of the Engineering Registration Law expires January 9, 1947, and that engineers whose needs eventually will require licensing should apply soon.

Present at the luncheon were Victor Siegfried (M '38) secretary of District 1; H. H. Henline, AIEE secretary, and C. L. Dawes (F '35) representing R. G. Porter of the committee on student activities. Representatives of the various Sections were as follows: Boston—F. S. Bacon, Jr., T. S. Gray; Connecticut—V. J. Hayes, E. G. Horton; Ithaca—E. M. Strong, W. H. Erickson; Lynn—C. B. Fontaine, M. A. Princi; Niagara Frontier—J. M. Geiger, J. D. Hershey; Pittsfield—J. C. Russ; Providence—C. H. Parker; Rochester—W. Criley; Schenectady—P. H. Light, B. H. Caldwell, R. V. Shepherd; Syracuse—C. E. H. von Sothen, L. J. Audlin; Worcester—A. L. Duna.

STUDENT CONFERENCE

Presentation of two prize-winning papers and an address on "Development Within the Profession," by Everett S. Lee (F '30) General Electric Company, Schenectady, N. Y., made up the program of Friday's student conference and technical meeting.

First prize of $15 for a student paper was awarded Thomas M. McCaw of Worcester Polytechnic Institute for his paper, "An Exposure-Color Temperature Meter." The meter, developed by Mr. McCaw to enable the color photographer to correct for the color temperature of light sources, depends on the interaction of two photoelectric cells, one red sensitive and the other blue sensitive. When exposed to light with a given color temperature, each will show a response, and the response of red to blue can be expressed as a ratio. The meter, however, has not been reduced to a physical size comparable with existing photoelectric exposure meters.

Second prize of $10 went to Henry Harper and Thomas E. Talpey of Cornell University for their paper, "Representation of Vectors on a Cathode-Ray Screen." The paper was presented by Mr. Talpey who described a method whereby a vector can be represented on a cathode-ray screen, its length proportional to the magnitude of the current or voltage it expresses, and its inclination to the horizontal proportional to the phase difference between it and some reference voltage of the same frequency. The method obviates the considerable amount of data and computations involved in plotting of the locus of a vector.

An interesting discussion among the approximately 40 students attending the conference followed each paper. Among the chairmen of Student Branches who attended were: R. W. Carpenter, Brown University; A. D. Sutherland, Cornell University; Richard Harris, Northeastern University; Aubrey Mitchell, Rensselaer Polytechnic Institute; J. W. Vorndran, Union College; and G. D. Keppert, Worcester Polytechnic Institute.

In his address to the students, Mr. Lee stressed the importance of affiliation with a national engineering society to an engineer who wished to extract the fullest benefits and chance for development from his professional life. Association with societies with more specific technical interests should and probably would come later in their careers, Mr. Lee told the students. In the same way he assigned affiliation with societies concerned with the engineer's relationship to society as a whole to a necessary but later stage in the career of the young engineer. He urged the students to set about planning to become registered engineers as soon as their state laws will allow. He advised them as citizens to become acquainted with their representatives in local, state, and federal bodies. As it is a problem with which they would be confronted upon entering industry, he also advised that the students study the material that has been collected and published on collective bargaining by the technical societies.

Professor R. G. Porter (F '44) of Northeastern University, chairman of the District committee on student activities, presided at the session.

SOCIAL EVENTS

An informal banquet preceded by a cocktail hour was held on Wednesday evening in the ballroom of the Hotel Statler. The principal speaker was the Honorable Orlo M. Brees, member of the New York State Legislature, whose subject was "The Secret of Happiness." R. R. McLeod, vice-president of the Buffalo Niagara Electric Corporation, was toast-master.

On Thursday evening a dinner and smoker was held in the Niagara Room. President Wickenden greeted the assemblage and commented on the good fellowship at the gathering, as well as that which exists between the 25,000 members of the Institute. Entertainment in the form of card tricks was provided by Mitchell MacDougall. Ted Rust gave a number of interesting ventriloquist demonstrations. G. M. Pollard (M '34) acted as toastmaster.

Annual Meeting

The annual meeting of the American Institute of Electrical Engineers will be held at the Hotel Statler, Detroit, Mich., at 10 a.m. Wednesday, June 26, 1946.

At this meeting, the annual report of the board of directors and the report of the committee of tellers on the ballot cast for the election of officers will be presented. The Lamme Medal will be presented to David C. Prince (F '26), and awards of Institute prizes will be announced.

Such other business, if any, as properly may come before the annual meeting may be considered.

(*Signed*) H. H. HENLINE
Secretary

Conference Hears Advantages of Statistical Quality Control

A well-attended conference, held April 25 at the North Eastern District meeting, at which five speakers presented methods and results of statistical quality control is reported by P. L. Alger (F '30) of the General Electric Company, whose long-standing interest in the subject has been reflected in his efforts at promoting conferences and providing material for *Electrical Engineering*.

In opening the conference the chairman, Professor M. A. Brumbaugh of the University of Buffalo, cited the growing importance of statistical methods throughout industry and recommended the series of educational articles currently appearing in *Electrical Engineering* as a good introduction to the subject.

Joseph Manuele (M '44) of Westinghouse Electric Corporation, outlined the procedure for initiating the use of modern quality control methods in quantity production. He explained the value of using a scientific sampling procedure, with careful measurement of each piece in the sample lot, to supplement or replace the old-fashioned 100 per cent inspection methods. In this way the average quality of inspected lots can be maintained at the desired level, and the risk of any given lot containing a greater than normal number of defectives always is known. Supplementing these sampling procedures by control charts at critical points in the production process, and backing them up by corrective action of engineers and planners, yield large dividends in reduced inspection costs and time saved, as well as in a higher quality.

He stated further that the production incentives of piece work rates can be supplemented by incentives to quality maintenance, if operators are provided with adequate gauges and devices for checking their own work. Allowance in the piece rates for this inspection time should be made, and operators then should be required to replace defective parts on their own time. In this way a single inspector who makes first piece inspections, checks samples from time to time, and gives help when needed, has maintained good quality in a section with as many as 67 production workers.

A. V. Feigenbaum, General Electric Company, described the separate steps of organizing a quality control program, and assuring co-operation of inspection, testing, and planning, as well as engineering and manufacturing heads. He stressed the need of teamwork in obtaining the desired quality in the most economical way. As examples of successful work, he described the methods used in producing aircraft voltage regulators and reverse current relays, where manufacturing losses and inspection costs were both reduced by one third in a four-month period, with even greater reductions in field troubles.

D. C. Stewart (M '35) Buffalo Niagara Electric Corporation, presented a statistical analysis of safety records in the light and power industry, showing that significant differences in company methods of accident prevention are indicated when the accidents of a particular company depart from the industry average by more than twice the standard deviation. He showed curves of total accidents, time lost, and fatalities plotted against millions of man-hours worked, which showed that better records generally were achieved by large companies with well-organized safety procedures.

E. H. Schneider (A '43) and J. M. Jesatko (A '41), Locke Insulator Corporation, cited a 40 per cent reduction in rework and an over-all saving of $6 per man hour spent on statistical quality control secured by application of these methods in insulator manufacture. Control charts of materials obtained from different vendors are maintained, as well as for critical factory processes; and field complaints have been greatly reduced.

A. J. Winterhalter, Colonial Radio Corporation, compared the performance in manufacture of a certain radio receiver before and after use of statistical quality control methods. Production was well stabilized on an apparently satisfactory basis, using the old inspection methods, in October 1943. At that time statistical methods were introduced. By January 1, 1944, the defects had been reduced 16 per cent, by June they were down 43 per cent, and by December 1944, they were 53 per cent lower than at the start. A recent attack on the particularly troublesome problem of soldered joints lowered the rework level in the past six months from 33 per cent to 13 per cent, with the sharp downward trend still continuing. Mr. Winterhalter also cited tests indicating that the average inspector on 100 per cent inspection work finds only 60 to 70 per cent of the defects, and many find even less; whereas with the more careful attention given to samples and the aid of statistical methods, a very much higher fraction of the defects is discovered.

In the discussion several speakers gave figures showing that 100 per cent inspection cannot be relied upon to eliminate defects, and that modern sampling methods with adequate first piece and process inspection are far superior. It was pointed out that statistical measures of the performance of individual operators, inspectors, and machines are proving very valuable in training and selection programs for workers, as well as in maintenance and replacement programs for equipment.

Future AIEE Meetings

Pacific Coast Convention
Seattle, Wash., August 27–30, 1946

Great Lakes District Meeting
Fort Wayne, Ind., September 25–27, 1946

STANDARDS . . .

Sixth Report Submitted on AIEE Aeronautical Standards

The progress made in aeronautical electrical standards work since the fifth progress report (*EE, Apr '45, pp 173–4*) and the status of AIEE participation as of April 24, 1946, are summarized herewith.

Aircraft Electrical Systems Subcommittee (Chairman, R. H. Kaufmann [M '41]). An additional section of the proposed report on "Aircraft Electrical Systems" has been completed in preliminary form, and every effort is being made to complete the other sections as soon as practicable.

Aircraft Electric Rotating Machinery Subcommittee (Chairman, M. L. Schmidt [M '43]). A comprehensive draft of a "Test Code for D-C Machines" has been edited and distributed to subcommittee members for review. This subcommittee expects to have a report ready for submission to the air transportation committee in June.

Aircraft Electric Control and Protective Devices Subcommittee (Chairman, R. A. Millermaster [M '34]). This group is maintaining contact with various developments in the field of aircraft electric control and protective devices. It expects to hold a meeting when the work of certain other groups makes such feasible.

Aircraft Wire and Cable Subcommittee (Chairman, W. S. Hay). The paper "Short Time Current Ratings for Aircraft Wire and Cable" by J. A. Scott (M '34) and B. W. Jones (M '43) has been scheduled for presentation and discussion at the AIEE summer convention in Detroit. The effect of groupings of cables, proximity to other equipment, high altitudes, and so forth will need to be studied to carry the analysis of wire and cable application on to a full conclusion.

Aircraft Carbon Brush Subcommittee (Chairman, V. P. Hessler [F '43]). Subcommittee members are preparing material and recommendations concerning specific items of the "Proposed Test Code for Aircraft Carbon Brushes," and a meeting is to be held in June to discuss a revision of the Summers–Stauffer report and to prepare a draft of the proposed test code for general distribution.

Subcommittee for Basic Principles of Altitude Rating (Chairman, W. E. Pakala [M '45]). The air transportation committee has set up a new subcommittee under the chairmanship of W. E. Pakala, Westinghouse Electric Corporation, East Pittsburgh, Pa., to develop an AIEE Standard covering the basic principles of altitude rating of aircraft electric machinery. Mr. Pakala is anxious to learn of persons who can contribute information or experience and to know of facilities that can be made available for experimental work. AIEE Standards coordinating committee 1 (P. L. Bellasch

(F '40) Westinghouse Electric Corporation, Sharon, Pa., chairman) is concerned with the general subject of altitude ratings.

Electric Equipment Safety. It has been decided not to form an air transportation subcommittee on this subject. It is understood that the Civil Aeronautics Administration is starting an extensive investigation of airplane fire control methods and related matters.

Aircraft D-C Apparatus Voltage Ratings (AIEE 700). This report on a proposed Standard has been on a trial basis for over one year and soon will be circulated by the AIEE air transportation committee for review as a possible full Standard.

NASC—Standard Method of Electrical Load Analysis for Aircraft (Chairman, K. R. Smythe [M '44]). Comments concerning the "Standard Method of Electrical Load Analysis for Aircraft" have been summarized and circulated to various interested persons. The Army Air Forces is now preparing tentative AN "Specification for A-C Load Analysis." WCAB is now preparing AN "Specification for D-C Load Analysis."

SAE Committee A-2, Aircraft Electric Equipment (Chairman, Edmund Thelan). The work of this committee was very ably piloted by C. C. Shangraw during the war period. He has found it necessary to resign the chairmanship because of the press of other work and Edmund Thelan, Eclipse-Pioneer Division, Bendix Aviation Corporation, Teterboro, N. J., has accepted the responsibility. This committee plans to reconsider present aircraft electrical standards in the light of new peacetime applications and to introduce new specifications where necessary.

Standard Corrected. The following errata are to be noted in AIEE Standard 45, "Recommended Practice for Electric Installations on Shipboard." Under "Third" in Sections 18.65, 18.67, 18.69, 18.81, 18.83, 18.85, change 0.136 inch to 0.115 inch. Errata sheets for insertion in the 1945 edition of the Standard can be obtained by writing to AIEE headquarters, 33 West 39th Street, New York 18, N. Y.

Telemetering Subcommittee Prepares Questionnaires

The joint subcommittee on telemetering, in connection with its assignment to revise the 1941 AIEE report, "Telemetering, Supervisory Control, and Association Circuits," has prepared a questionnaire on telemetering apparatus and systems. This questionnaire, designed to obtain the basic data necessary to make an authoritative revision, has been mailed to the industry with as broad a distribution as the knowledge of the committee permitted. It is requested urgently that any manufacturer or distributor of such apparatus who has not received this questionnaire apply to AIEE headquarters, 33 West 39th Street, New York 18, N. Y., for copies.

A similar questionnaire on supervisory control systems is in the course of preparation and will be mailed in the near future. At present the committee has only a limited list of manufacturers or distributors of this equipment and so requests that all companies sponsoring such systems, which are not represented in the 1941 report, so advise the chairman, G. S. Lunge, General Electric Company, 1 River Road, Schenectady 5, N. Y., so that they may receive copies of the questionnnaire.

SECTION • • • • • •

Loran Navigation Is Topic At Final Philadelphia Meeting

The last of its meetings for the 1945–46 season was held by the Philadelphia Section, Monday, May 13, in the Engineers Club in Philadelphia, Pa., with an attendance of 145.

A review of the year's high lights in Section activities was given by C. T. Pearce (M '40) retiring chairman. These included the passing of the 1,000th member milestone, which represented a growth in membership in excess of 10 per cent during the year; the establishment of a basic science discussion group; the total of 42 meetings in all activities of the Section; and the establishment of additional committees on suggestions, section history, and Princeton–Trenton meetings. The efforts of the Wilmington Subsection and of the communications discussion group were given special mention.

Officials elected for the 1946–47 season were:

H. A. Dambly (F '42) *chairman;* E. W. Boehne (F '43) *vice-chairman;* W. R. Clark (M '44) *secretary;* and C. S. Schifreen (M '43) *treasurer.*

Following the short business session, J. A. Pierce of the Cruft Laboratory, Harvard University, spoke on "Loran—Long Range Navigation." The Loran system has been extended to cover three-tenths of the earth's surface, according to Doctor Pierce who gave the history of the development and outlined the fundamental concepts of hyperbolic navigation. Details of equipment in service and of future trends and potential uses were given. A film showing the routine methods of calculating position from oscillograph readings followed the talk.

As the final one of the season, the meeting closed with the usual award of attendance prizes by the fellowship and attendance committee, headed by J. E. Johnson (M '45). Numerous appropriate gifts had been presented to the committee for the occasion. As a method of awarding these prizes, a judge and a sergeant-at-arms were chosen by drawing. After these officials were suitably costumed, they supervised the drawing of names by lot from a mixing drum. Each winner had to prove his worthiness to receive a gift by some special stunt on the merit of which the judge and sergeant-at-arms were final authority.

New York Section Closes Extremely Active Year

As part of its accounting at the close of its administrative year, the New York Section recently assembled an impressive set of figures on meetings and attendance.

A total of 262 meetings attracting an attendance approximating 28,000 were sponsored by the Section in an 8-month period. Thirty regular Section meetings were arranged by various technical groups and program committees, and 232 were connected with the 21 courses conducted by the Section in special fields of current interest and in review of fundamentals as preparation for engineers' licenses. Attendance at the regular meetings totaled 6,900 and at the others, 21,000. This gives an average of 1.5 meetings for every weekday during the period covered by the tabulation. In addition, 26 conferences were held to give counsel to returning veterans, with an attendance of almost 700.

Fairman Addresses Lynn Annual Dinner Meeting

As guest speaker at the annual dinner of the Lynn Section held April 30, at the Thomson Club, Nahant, Mass., J. F. Fairman, AIEE vice-president, considered the topic, "Organization of the Engineering Profession."

Mr. Fairman discussed the recent report of the AIEE subcommittee on professional activities (*EE, Apr '46, pp 169–73*) and distributed a questionnaire prepared by the subcommittee. Following his address discussion continued for nearly an hour, and the Section membership expressed a strong interest in and enthusiasm for the work being done by the committee on planning and co-ordination through its subcommittees.

Approximately 200 members and guests attended the dinner.

Meetings of New Subsection of Lancaster–York Well Attended

The Lancaster–York Subsection of the Maryland Section was organized early in 1945 to relieve Section members living in Lancaster, York, and Adam Counties of Pennsylvania from the necessity of making the 60-mile trip to Baltimore under wartime difficulties.

A preliminary meeting was held in Lancaster, July 12, 1945, when tentative plans were made and a functioning committee organized. This committee called a meeting for September 13, when the final

organization of the Subsection was completed with 23 members present. The following officers were elected: R. W. Larsen, *chairman;* H. J. Stewart, (A '38) *vice-chairman;* J. L. Stauffer (A '24) *secretary-treasurer.* Since this meeting the membership has grown to 172. Six meetings have been held, four at Lancaster and two at York, with an average attendance of 112. It is evident that this Subsection is filling a real need.

Michigan Arc Display Draws Large Audience

A display of arcs, mainly at utilization voltages, was featured on the program of two evening meetings of the AIEE Michigan Section held in the laboratory of the Bull Dog Electric Products Company, Detroit, April 24 and 25.

Sponsored by the industrial power group of the Michigan Section in co-operation with the Industrial Electrical Engineering Society, a Detroit organization of plant operating engineers, a two-hour program of 30 scheduled items, ranging from small sparks to explosive arcs and including the destruction of unprotected 440-volt devices, was presented.

Speaker at the meetings was Lawrence E. Fisher (M '38) director of research, for the Bull Dog Electric company, who presented technical data and necessary explanations on the tests performed. Tests included arcs on insulators and the spraying of salt water and iron dust on energized plug-in duct. Movies taken by an ultra-high speed camera and timing clock showed slow-motion detail of arc interruption by circuit breakers and the periodic fluctuation of a 60-cycle maintained arc.

Approximately 140 attended each meeting and were dinner guests of the Bull Dog Electric company preceding the demonstrations. D. D. Douglass (M '44) chairman of the industrial power group headed the committee which arranged the meetings.

Philadelphia Announces Awards in Prize Paper Contest

In its 1945–46 prize paper competition the Philadelphia Section recently awarded three best paper prizes, one for each of its geographical divisions, Philadelphia, Delaware, and New Jersey. Prizes also were awarded for the best initial paper and honorable mention was given two papers.

Authors names and titles of the winning papers follow:

First Prize

Philadelphia division: "Application of the Ohm and Mho Principles to Protective Relays" by A. R. van C. Warrington (M '43).

Delaware Subsection: "Electrical Construction—Material and Time-Saving Methods" by R. G. Rudrow (M '41).

New Jersey division: "Salesmanship in Engineering" by R. T. King (M '37).

Best Initial Paper

"Coincidence Factor Relationship of Electric-Service-Load Characteristics" by Constantine Bary (M '43).

Honorable Mention

"Research on Aids for the Blind" by Thomas A. Benham (A '39).

"The Development, Design and Performance of Magnetic-Type Power Circuit Breakers" by B. W. Wyman (A '40), and L. J. Linde (M '45).

Illinois Valley Section Reports First Year's Activities

A total of 11 formal meetings held during the Illinois Valley Section's first year of operation is reported by Professor F. E. Dace (M'43), Section chairman. These were interspersed by technical groups meetings, attendance at which sometimes outnumbered that at regular Section meetings, according to Professor Dace.

Two of the Section meetings were held in Springfield, two in Pekin, and others in Peoria. The Section also has taken an active part in the Peoria Engineering Council, which represents 19 engineering organizations.

The Section's annual meeting, held May 4, was addressed by AIEE President W. E. Wickenden. The April 4 meeting was held on the campus of Bradley Polytechnic Institute, and the speaker for the evening and the members of the executive committee were guests of the college at dinner.

Joint meeting of the AIEE Michigan Section and the IEES in the electrical laboratory of the Bull Dog Electric Products Company, Detroit, April 24, 1946

ABSTRACTS . . . .

TECHNICAL PAPERS previewed in this section will be presented at the AIEE summer convention, Detroit, Mich., June 24-28, 1946 and will be distributed in advance pamphlet form as soon as they become available. Copies may be obtained by mail from the AIEE order department 33 West 39th Street, New York 18, N.Y., at prices indicated with the abstract; or at five cents less per copy if purchased at AIEE headquarters or at the convention registration desk.

Mail orders will be filled

AS PAMPHLETS BECOME AVAILABLE

Air Transportation

46-129—Electronic Control of Frequency Converter Sets for Testing Aircraft Models; *G. W. Heumann (A '44), W. F. Strang (A '41). 25 cents.* The paper describes the 65- to 400-cycle variable frequency a-c power system used for testing aircraft models in the United Aircraft Corporation wind tunnel at East Hartford, Conn. Induction type frequency converters, driven by d-c shunt motors with armature voltage control, supply variable frequency power. Electronic exciters energize the various d-c fields, and electronic regulators are described in detail for control of speed, current limit, volts per cycle, and load division during parallel operation of two converter sets. Antihunt circuits insure stable operation. The power system is used for speed control, by frequency control, of high-speed induction motors driving propellers. Aerodynamic performance is determined by precision measurement of speed and electric input into the model motors which, from motor calibration data, permit computing the mechanical input into the propeller. The electric controls enable the operator to obtain any test point within the range of the equipment.

46-131—Investigation of Porcelain Insulators at High Altitudes; *C. V. Fields (A '41), C. L. Cadwell. 15 cents.* The use of high voltage apparatus in military aircraft made it necessary to obtain flashover data on capacitor bushings at altitudes up to 50,000 feet. Some of the more pertinent data are presented in this paper which gives a-c and d-c flashover voltages for porcelain bushings having spacings of 5/8 inch to 2 1/2 inches from cap to ring. The tests were made at both normal atmospheric and reduced pressures, but no attempt was made to simulate the frosting conditions as encountered in flying. Correlations are shown between bushing spacings and the effect of pressure change. A single correction curve for pressure changes cannot be used, but a family of curves is required for various spacings of insulators

and electrostatic field configuration. This paper shows that the practical use of porcelain insulators is limited to altitudes and voltages well below maximum values proposed for aircraft use. It is recommended that solid insulation be used in such a manner as to obtain the benefit of its puncture strength rather than its flash-over at the more extreme conditions of altitude and voltage.

46-145—Short-Time Current Ratings for Aircraft Wire and Cable; *B. W. Jones (M '43), J. A. Scott (M '34).* *15 cents.* This paper gives the results of a series of tests on two sizes (AN-16 and AN-8) of insulated aircraft wires and cables which were made to determine their permissible short-time current carrying capacities. The times under consideration ranged from 0.01 to 1,000 seconds. A description is given of a very simple but adequate electrical test, together with an accompanying insulation test, to determine what are considered permissible transient temperatures. Tentative recommendations of short-time current carrying capacity for aircraft cable sizes AN-22 to AN-00 are made.

46-148—A Unique Engine Synchronism Indicator for Aircraft; *D. B. Pearson (A '41).* *15 cents.* Greater passenger and crew comfort, improved flight efficiency, and minimized vibrational stresses are obtained by exact synchronism between the engines of multiengine aircraft. Much closer synchronism than is attainable with engine tachometers alone can be provided by using suitable synchronism indicators. The limited panel space available has dictated a very compact construction for synchronism indicators without sacrifice of accuracy or dependability. This has been accomplished by designing an indicator mechanism which utilizes a principle similar to that of electric-power-circuit synchroscopes, but which is much smaller in size. The construction and operating characteristics of this unique aircraft engine synchronism indicator are described.

Automatic Stations

46-106—Automatic Control of Large Synchronous Condensers; *M. J. Brown (M '44).* *30 cents.* The considerations involved in the design of an automatic synchronous condenser control are discussed in this paper with an aim toward helping the designer and user of synchronous condenser equipment obtain modern and complete facilities in his design. A typical push button operated control for a large synchronous condenser is described, and the diagrams involved are shown. The description includes a detailed résumé of starting sequence, protective device operation, and automatic control of voltage and load. Emphasis is put on the adaptability of push button control to full automatic operation or remote operation by direct or supervisory control.

46-147-ACO—Operating Experience With Single Pole Switching; *I. T. Knight (M '42).* *15 cents.* Single pole and two pole switching provide greater transient stability of interconnected systems. During swings, power is transferred through the grounded neutrals and over the phases remaining closed, alleviating stresses in generator equipment. The selection of the tripping circuits, together with the high speed carrier distance relaying and 20-cycle reclosing, necessarily complicates the control. However, complications are justified when it is considered that the purpose of the interconnection is to supplement generator capacity. Oscillograms and tables show the performance during testing with mimic power faults and load conditions.

46-174—Carrier Supervisory Control of Pumping Station Over Power Cable; *W. A. Derr (A '43), W. A. Keller, H. A. W. Hedke (A '34).* *20 cents.* A recent installation of power-line carrier supervisory control provides for unattended operation of a pumping station in Lake Okeechobee. The pumping station provides the necessary water for a new starch plant of the United States Sugar Corporation. In addition to providing for the remote control of apparatus units, the supervisory control also provides selective telemetering and communication over the same single-frequency carrier channel. The carrier equipment operates over 4,000-volt power cable, part of which is rubber jacketed and part of which is armored submarine cable. The paper presents field test data on the attenuation values of the cable. The use of low-voltage capacitors similar to standard power factor correction capacitors instead of standard carrier coupling capacitors is described. The incorporation of the carrier and supervisory control equipment in a metal-clad switchgear assembly also is described.

Basic Sciences

46-110—The Influence of the Concentration and Mobility of Ions on Dielectric Loss of Insulating Oils; *B. P. Kang (A '40).* *20 cents.* The purpose of this study is to help in clarifying one phase of the picture on the nature and mechanism of dielectric loss in insulating oils. It deals with the relations of dielectric loss on one hand and the concentration and mobility of the free ions on the other. To vary the concentration and mobility of ions, different percentages of a highly deteriorated oil were added to two highly refined oils of different viscosities. It was found that the dielectric loss varied inversely as a function of the viscosity logarithmically. If mobility of the ions is kept constant, the dielectric loss will be a linear function of the content of free ions in the oil. On the other hand, an increase in the concentration of ions in an oil may result in an actual decrease in dielectric loss, if the viscosity is increased to the point where the mobility of the ions is decreased relatively more than the ion concentration is increased.

46-111—A Fractional Termination for Ladder Networks; *Wilbur R. LePage (M '44).* *20 cents.* By use of a uniform ladder network to simulate a smooth transmission line of sufficiently small electrical length, a termination intermediate between the ordinary mid-series and mid-shunt types is derived which is superior to the latter types. The superiority lies in a reduction of the errors of the four-terminal-network parameters, as compared with those for the smooth line, and in the reduction of the distinction between the mid-shunt and mid-series terminations. The new termination may have use when simulating lines shorter than a quarter wavelength. Formulas for the new terminations, and estimates of the errors of the parameters, are given for networks of any number of sections, but the results are of most practical value when there are few sections. It is found that no improvement is possible by modifying the next-to-the-terminal elements of the uniform network.

46-119—Formulas for Calculating the Inductance of Channels Located Back to Back; *W. G. Schwantz (Student), T. J. Higgins (A '40).* *25 cents.* Formulas are derived for calculating the inductance of a bus comprised of two identical channels located back to back. It is assumed that the conductors are nonmagnetic, are of such length that end effects are negligible, are right cornered, are uniformly thick, and carry currents distributed uniformly over their cross sections. On these bases a general formula is obtained through use of geometric mean distance theory. An approximate formula, suitable for preliminary computation, stems from considering conductors infinitely thin rather than uniformly thick. Once these formulas are derived, their use is illustrated by calculation of several typical problems. Additional problems illustrate precautions to be observed in using the approximate formula.

46-120—Negative Resistance Effects in Saturable Reactor Circuits; *J. M. Manley, E. Peterson (M '26).* *30 cents.* Sustained oscillations exhibiting many of the properties of free oscillations are found in saturable reactor circuits under appropriate conditions. The frequencies of such oscillations are classified in relation to that of the driving source as

1. Incommensurable.
2. Subharmonic and multiples thereof.
3. Harmonic.

General properties of the oscillations classified are elucidated by reference to an analysis of R. V. L. Hartley's dating back to 1917. In part I a comparatively simple form of analysis is used to demonstrate the development of negative resistance by what is essentially a modulation process. Applications then are made to the three classes of oscillations just listed. Some of the simplifying assumptions of part I are removed in part II to approximate practical conditions more closely for the evaluation of a specific product: the third subharmonic. Quantities evaluated over

wide ranges of the variables involved include the impedance of the nonlinear coil to the subharmonic, the subharmonic amplitude, its stability, and the conditions required for starting and maintaining the oscillation. Experimental data are found in general agreement with the results of computation.

46-128—A New Approach to Probability Problems in Electrical Engineering; *H. A. Adler (M '44), K. W. Miller (M '29). 15 cents.* In many electrical engineering problems the probable durations of simultaneous events and the probable intervals between such simultaneous occurrences are of great importance. The usual mathematical formulas and available methods determine only the probability or ratio of time occupied by simultaneous events, without specifying either their durations or intervals between recurrence. This paper presents formulas useful for determining average durations and intervals between simultaneous events for a variety of conditions encountered in engineering problems.

46-130—Dimensionless Analysis of Servomechanisms by Electrical Analogy; *S. W. Herwald (A '45), G. D. McCann (M '44). 15 cents.* This paper gives the results of a general study that has been made of standard forms of angular position servomechanisms. The rapidity with which complete transient solutions can be obtained on the mechanical transients analyzer has permitted the analysis for a wide range of servomechanism parameters. These data are plotted in dimensionless form, permitting the ready determination of the performance of a given servo system or the selection of parameters for optimum performance.

Communications

46-151—Mica Capacitors for Carrier Telephone Systems; *A. J. Christopher (A '28), J. A. Kater. 15 cents.* This paper discusses the types of mica capacitors used in carrier telephone systems in the Bell telephone plant. It covers the construction and some of the more important electrical characteristics of the silvered mica capacitors currently used in oscillators, networks, and other frequency determining circuits because of their inherently high capacitance stability with temperature changes and with age. Their use in place of the previous dry stack type, consisting of alternate layers of mica and foil clamped under high pressures, has made possible considerable manufacturing economies in addition to improving the transmission performance of carrier telephone circuits. The manufacturing economics are the result of relatively simple unit construction and ease of adjustment to the very close capacitance tolerance required.

46-161—Systems Development of Military Communications; *T. R. Putnam (M '45). 15 cents.* The broad phases of the problems involved in developing the land line network of signal communications required for extensive land and land-based air operations into a theater-wide system are discussed. The basic nature of both tactical and rear area communications are described and compared with commercial systems from an operating standpoint. The aspects reviewed are those concerned with unification of control of the over-all network under the handicap of War Department signal communication doctrine. The solution to the problem of developing the theater-wide network into a unified system in the North African theater of operations is given, together with some operating results.

46-162—Properties and Uses of Thermistors—Thermally Sensitive Resistors; *J. A. Becker (F '43), C. B. Green, G. L. Pearson. 30 cents.* A new circuit element and control device, the thermistor or thermally sensitive resistor, is made of solid semiconducting materials, the resistance of which decreases about four per cent per centigrade degree. The thermistor presents interesting opportunities to the designer and engineer in many fields of technology for accomplishing tasks more simply, economically, and better than with available devices. Part I discusses the conduction mechanism in semiconductors and the criteria for usefulness of circuit elements made from them. The fundamental physical properties of thermistors, their construction, their static and dynamic characteristics, and general principles of operation are treated. Part II of this paper deals with the applications of thermistors. These include: sensitive thermometers and temperature control elements, simple temperature compensators, ultrahigh frequency power meters, automatic gain controls for transmission systems, voltage regulators, speech volume limiters, compressors and expanders, gas pressure gauges and flowmeters, meters for thermal conductivity determination of liquids, and contactless time delay devices. Thermistors with short time constants have been used as sensitive bolometers and show promise as simple compact audio frequency oscillators, modulators, and amplifiers.

46-163—Transmission Rating of Telephone Systems; *W. A. Codd. 15 cents.* The problem of rating the transmission performance of telephone connections is considered, including a review in considerable detail of a method proposed by J. R. Hughes for "The Comprehensive Assessment of Telephone Communication Efficiency." A modification of Hughes' technique is presented with indications of certain attendant advantages.

Electric Machinery

46-116—Electromechanical Transient Performance of Induction Motors; *C. N. Weygandt (A '37), S. Charp (A '42). 30 cents.* Two phase induction motors commonly are used as servo motors because they can be reversed and controlled readily. Although they are extensively employed, such utilization is mainly on an "it works" basis. This paper is the result of a differential analyzer study of their starting and reversing characteristics, based upon solutions to the induction motor equations formulated by H. C. Stanley in 1938. These performance equations are solved, and summary curves based upon the conclusions reached are presented in a form useful to the motor designer. A comparison of the theoretical results with experimental data of an actual motor is made. No published data of the type presented in this paper have come to the attention of the authors.

46-136—Current and Torque of D-C Machines on Short Circuit; *T. M. Linville (M '34). 30 cents.* An analysis of d-c machines under short circuit is made, and formulas are derived for the armature current, field current, and torque. The formulas are applied to several machines and the calculated results compared with test data. The terms of the formulas can be evaluated easily, and in many cases, particularly with large machines having bar windings, approximate calculations can be made without need of manufacturer's data. The paper is useful in problems concerning the protection of machines and circuits against the abnormal currents and forces produced by short circuit. Important features of the paper are:

1. The expression for the relation between electromotive force, armature amperes, and field amperes.
2. An expression for the resistance to current flow created by the reactance voltage of the alternating current in the armature winding.
3. A formula for estimating the time constant of the armature circuit using an average coefficient of inductance.

46-157—Factors Affecting Insulation Resistance of Large D-C Machines; *J. S. Johnson (M '45), Conrad Weil (A '44). 25 cents.* Insulation resistance data of 1,100 new d-c machines in the range of 1,000 to 7,000 horsepower are analyzed. Estimates are made from a statistical study of the data and known machine design proportions of the relative magnitudes of the principal factors which affect the insulation resistance of new d-c machines. In addition to previously recognized factors, such as material resistivity, insulation temperature, and machine size, the absolute humidity of the surrounding air is shown to affect significantly the insulation resistance of commutator type machines. Based on this study, a simple linear insulation resistance formula for new d-c machines is developed which includes corrections for the effects machine size and the absolute humidity of the surrounding air at the time of test. Since the voltage range of large d-c machines is small, the rated machine voltage has been omitted in the suggested formula.

46-164—Oscillations of a High-Voltage Secondary Winding; *A. Boyajian (F '26). 30 cents.* Rational design of transformer insulation requires knowledge of the distribution of stresses under abnormal conditions. This problem has been analyzed fairly completely for the case in which the

disturbance is applied directly to the terminals of a winding. However, there is a need for a more complete analysis for the case when the disturbance is induced in a winding acting as a secondary winding. This paper presents a novel theory and outlines the method of analysis. A feature of the theory is that the natural mode of the oscillations of such a circuit are not quarter waves or half waves and their multiples, but intermediate fractions of waves. The paper gives methods of estimating the overvoltages as functions of such harmonics and explains how to determine the characteristics of the transformer for use in the calculations.

46-165—Temperature Limits for Short-Time Overloads for Oil-Insulated Neutral Grounding Reactors and Transformers—II; *V. M. Montsinger (F'20), J. E. Clem (F'38). 25 cents.* In part I, published in 1938, the principal question considered was the effect of ventilating coils on temperature limits for ground faults greater than one minute, for which it was assumed that 160 degrees centigrade based on all heat stored in copper only, was the correct limit. Since 1938 considerable new data have been obtained. This paper presents the new data and shows that:

1. For heating periods of one minute or less, practically all aging of insulation occurs during the cooling period. It is shown that temperature limits can be based on the "rate of cooling," rather than on the heating period.

2. In the heating period of one minute or less 25 to 45 per cent of the loss is dissipated from the copper to the insulation and oil. Formulas are developed for calculating the temperatures during the heating and cooling periods.

3. Temperature limits above 160 degrees centigrade for one minute are permissible for both nonventilated and ventilated coils, being approximately 200 degrees centigrade for windings which cool sufficiently rapidly.

46-166—Some Aspects of Polyphase Motor Design—The Design and Properties of the Magnetic Circuits; *T. C. Lloyd (M'46), H. B. Stone. 30 cents.* By comparing a great number of laminations used successfully for a number of years in polyphase induction motors, and taking into account various theoretical factors, rules are formulated for determining dimensions of a series of laminations. The theoretical determination of a best lamination involves a fixed number of poles; the method shown indicates means of obtaining average laminations for a range of usefulness, as well as designs for various poles. The maximum torque of a given lamination designed for a number of poles is indicated, as well as the inherent volt-ampere capacity. A liberal number of examples is used to illustrate the influence of lamination proportions on motor performance.

46-167—Rotating Electric Machine Time Constants at Low Speeds; *C. Concordia (M'37). 20 cents.* This paper presents the results of a study of the variation of the several time constants of electric machines with rotor speed. Previously, formulas for machine time constants at rated speed and at standstill have been used. As these time constants are quite different at these two speeds, it becomes important to show the way in which they vary continuously as the speed increases from standstill, and to determine proper values for use at very low speeds.

Electric Welding

46-137—Influence of Magnetic Materials on the Welding Characteristics of Resistance Welding Machines; *J. J. Riley, C. E. Smith (M'44). 25 cents.* The insertion of magnetic materials, such as steel sheets, into the throat of a resistance welder causes a reduction in the welding current. The degree of reduction and simple mathematical tools for estimating it are derived. The effect on welding current of thickness of sheets, of inserted length, of position in the welder throat, of width of sheets, and of magnitude of welding current were investigated. The change in welding current was evaluated by measuring the reactive and resistive voltage components caused by the steel sheets in the welder throat and summarizing them in nomogram form. This chart in combination with the short-circuit impedance constants of the welder provide the working tools. The effect of welding steel sheet independent of steel inserted in the throat also was investigated to complete the analysis of determining welding current changes in terms of circuit variables.

46-141—The Application of Series Capacitors to Flash Welders; *J. F. Deffenbaugh (A'42). 15 cents.* The application of series capacitors to spot, projection, and seam welders no longer presents any difficult problems, and such capacitors have been used successfully with these types of welders for several years. Essentially, enough capacitive reactance is placed in the primary circuit of the welder transformer to neutralize the inductive reactance of the welder. This theoretically produces unity power factor and reduces the kilovolt-ampere demand to the level of the kilowatt demand. Since the voltage across the capacitor units is directly proportional to the current flowing through them, units must be selected with a voltage rating high enough so that this rating is not exceeded, unless they are protected by an overvoltage device. The flash welder, however, presents an entirely different problem, as the welding operation is composed of two phases which differ widely in both power factor and kilovolt-ampere demand.

46-156—Characteristics of Resistance Welding Transformers; *F. E. Murray, R. C. Jones. 15 cents.* This paper deals with the practical design of resistance welding transformers. It is the authors' desire to convey to the readers the general characteristics and problems encountered in design. The material covered has been presented with the thought in mind that it will enable users of resistance welders to understand better this vital part of their equipment. A portion of the paper covers a sample design of a resistance welding transformer. This section contains a general picture of the design constants used in determining core and copper sections.

Electronics

46-105—Inductive Co-ordination Aspects of Rectifier Installations; *An AIEE Committee Report. 30 cents.* This report presents methods of classifying proposed installations from the inductive co-ordination standpoint, simple approximate methods of estimating harmonics in a-c systems associated with the operation of rectifier installations, and other information dealing with the inductive co-ordination aspects of rectifier installations.

46-126—Fundamental Properties of the Vacuum Switch; *R. Koller (A'43). 25 cents.* A study has been undertaken of the basic mechanism affecting the interruption of currents in high vacuum. The interruption starts as an ordinary vapor arc which is quickly deionized by a fast radial gaseous diffusion in the evacuated space. This first arc is followed by a series of short periods of extinction interspersed with arc bursts of microsecond duration. Cold emission restrikes and magnetic self-focusing are also active. The cathode loses material by sputtering. The main factors affecting this loss are: the current, the recovery voltage, the electrode material, the shape of the cathode, and the opening speed. The switch operates below 10^{-4} millimeter of mercury pressure. The sputtering acts to reduce the pressure due to gases and vapors evolved from the electrodes, by a combination of getter action and diffusion-pump-like action. A constant working pressure thus can be established.

46-138—Excitation, Control, and Cooling of Ignitron Tubes; *C. C. Herskind (M'40), E. J. Remscheid (M'40). 15 cents.* A description of the excitation, control, and temperature characteristics, limitations, and requirements of typical ignitron tubes is presented. Oscillographic tests show the grid action throughout the cycle. The control characteristics provided by the grid depend upon these arc processes. The procedure for specifying the limitations and requirements of the tubes as regards excitation, control, and cooling is outlined.

46-139—Rectifier Capacity; *C. C. Herskind (M'40), H. C. Steiner (M'44). 15 cents.* The application of mercury pool tubes to a variety of rectifier units having different circuits and ratings requires a knowledge of both the circuit duty and the rectifier capacity. The procedure for the determination of rectifier capacity and the application of rectifier tubes on the basis of such data is described. The relation between voltage, current, phase control, reactance, and rectifier capacity are shown. Tests and experience indicate that phase control is an important factor affecting rec-

tifier capacity. Curves showing the capacity characteristics of two typical ignitron tubes are presented.

46-140—A 400-Ampere Sealed Ignitron; *H. C. Steiner* (*M '44*), *H. N. Price*. *20 cents*. As rectifier capacity is increased, it becomes desirable to use larger capacity rectifying elements. The choice of rectifying element size requires careful consideration in order to provide a complete range with a minimum number of units. The sizes of industrial ignitron tubes for welding control and for rectifier service have been chosen on a preferred number scale, providing a proportionate increase at each increment. The development of a 400-ampere ignitron for rectifier service was undertaken to provide the next larger size tube in the series. Development work disclosed that design problems become more complex as the physical size of the tube is increased. However, none of the factors involved have indicated an upper limit in size but rather a need for a more exact understanding of the phenomena involved.

46-143—Nonlinear Commutating Reactors for Rectifiers; *A. Schmidt, Jr.* (*M '45*). *15 cents*. The factors involved in rectifier duty are discussed, and it is shown that increased reactance results in decreased rectifier duty. The same result may be obtained from suitable presaturated nonlinear reactors with less accompanying regulation as compared with linear reactors. The design of nonlinear reactors is discussed, and the circuit action of typical reactors is indicated. An example is given of the increase in rectifier rating which may result from the use of commutating reactors under severe duty conditions.

46-146—Circuit Cushioning of Gas-Filled Grid-Control Rectifiers; *D. V. Edwards* (*A '37*), *E. K. Smith*. *15 cents*. In certain common rectifier and inverter circuits, gas-filled rectifier tubes, supplying highly inductive loads with firing delayed by grid control, are subjected to the application of high rates of rise of initial inverse voltage. This phenomenon results in short tube life because of the sputtering of anode material by the impact of residual ions attracted to the negative anode with consequent gas cleanup. The paper describes a method of slowing down or "cushioning" the rate of rise of initial inverse voltage. A small resistance and capacitance circuit connected between cathode and anode delays the voltage rise the few microseconds necessary to eliminate sputtering. Life test data and practical applications are cited which confirm the elimination of gas cleanup.

Induction and Dielectric Heating

46-124—Design of Induction-Heating Coils for Cylindrical Magnetic Loads; *J. T. Vaughan* (*A '44*), *J. W. Williamson* (*A '43*). *20 cents*. Equations are presented by means of which the authors' previous paper "Design of Induction-Heating Coils for Cylindrical Nonmagnetic Loads" is extended to the design of coils for heating magnetic loads, where the load remains in a fixed position relative to the coil during the heat. In heating magnetic materials there is considerable variation in impedance of the coil circuit as the load temperature changes. The present paper first develops certain general principles by means of which a variable impedance circuit may be designed to absorb a predetermined maximum power, on the basis of constants determining the maximum and minimum impedance. Methods then are given by means of which these constants may be calculated for carbon steel loads of types SAE 1015-SAE 1045 or equivalent. In practice these methods apply to most through-heating and some surface-heating applications. The accuracy of calculations is substantiated experimentally.

46-153—Low-Reactance Flexible Cable for Induction Heating; *Myron Zucker* (*M '36*). *15 cents*. A flexible water-cooled cable, designed primarily for portable spot welders, has been used for supplying power to induction heating coils at about 1,000 and 10,000 cycles. The increased voltage drops and power losses at the higher frequencies are especially important because of the relatively small current transmitted. Therefore, tests and calculations were made to determine the electrical characteristics. These are affected by the amount of copper in the cable and the number of parts into which the copper is divided. Inductive reactance, which is the most important factor, is computed and checked with reasonable accuracy. Approximations are available for other electrical characteristics. Formulas are obtained by which cable performance can be anticipated. These will be used where there is a demand for the flexible cable to supply power in the low-voltage kilocycle-frequency range.

Industrial Control Devices

46-104—Silicone-Resin-Treated Magnet Coils; *G. L. Moses* (*M '44*), *J. J. Torok* (*M '35*). *20 cents*. Silicone insulation was investigated on magnet coils to parallel similar tests on motors. Laboratory tests are reported with standard coils. These tests covered the range between 200 and 275 degrees centigrade. These were aimed to determine the life-temperature characteristics and to evaluate the design advantages.

46-113—Electrical Accuracy of Selsyn Generator-Control Transformer System; *Harold Chestnut* (*A '41*). *30 cents*. The military requirements for high accuracy position control systems have resulted in the development of the Selsyn generator-control transformer system which indicates electrically a mechanical shaft position. This signal source is dependable, capable of continuous rotation, and has a high inherent accuracy, although it is not completely error free. To determine the cause of inaccuracies in electric transmission, the system was studied

(a). Under static operation.
(b). Operating at constant velocity.

The effect on errors of such factors as unbalanced resistance or reactance, salient pole construction, and velocity has been determined. The dominant effect of unbalance resistance in a stator phase or in the lines between machines is to introduce an out-of-phase component of "error" voltage. However, reactance unbalance in the stator phases or certain harmonics of mutual reactance between rotor and stator produce a position error. Operation of the system at constant velocities comparable with the synchronous speed for excitation frequency employed produces an appreciable out-of-phase error voltage. However, at lower speeds of operation the error is primarily a position error in transmission, amounting to about 1 degree for 320 rpm.

46-125—An Electronic Drive for Windup Reels; *K. P. Puchlowski* (*A '43*). *20 cents*. This paper gives a description of an electronic system which automatically controls the speed of the takeup reel motor in such a manner as to provide an essentially constant strip speed during the reeling operation. The system also provides means for selection of the strip speed within a wide range. The power supplied from an a-c line is rectified and controlled by the electronic system, and then is supplied to a conventional d-c shunt wound motor which drives the windup reel. With the exception of a small tachometer generator which indicates the speed of the strip, the main driving motor is the only rotating machine used in this drive. The paper also includes a general discussion of the operating principles of servo systems and emphasizes these principles in the description of the drive.

46-130—Dynamic Braking Control of D-C Series Motors—Calculation of Stability Limit; *G. W. Heumann* (*A '44*), *W. P. Smith*. *15 cents*. This paper presents an extension of the conventional method of calculating speed-torque curves for d-c series motors used with dynamic braking controllers. By means of test data, it is shown that torque per armature current and electromotive force per speed are a function of both field and armature current. With low field currents, armature reaction limits the maximum braking torque the motor is able to deliver. A per unit method is given to calculate stability limit. It is shown that the stability limit can be increased by the use of external series resistance.

46-132—Electronic Register Control for Multicolor Printing; *W. D. Cockrell* (*M '43*). *20 cents*. The popular illustrated magazines of today are printed on high speed rotogravure color presses. For acceptable pictures, the colors must be superimposed on one another, or registered, to a tolerance of a few thousandths of an inch in spite of paper stretch and shrinkage due

to tension changes and the necessary drying of each color between impressions. The two requirements of accurate register and high speed operation are met by an all-electronic register control system. In this paper a system is described in which electronic tubes perform all functions. Photoelectric tubes compare the relative positions of the printing cylinders and the incoming web. Pliotrons comprise the amplifier, comparison, and control circuits, and thyratron circuits supply the armature power to the reversing motor used to correct the position of the printing cylinder or compensating roll.

Industrial Power Applications

46-122—Protection of Industrial Plants Against Insulation Breakdown and Consequential Damages; *H. R. Vaughan (M '41). 15 cents.* Experience has shown that several electrical failures may occur simultaneously in an industrial plant as the result of a breakdown of insulation, causing high transient voltages. Available methods of surge protection to guard against insulation breakdown and neutral grounding to prevent high transient voltages are presented. Consideration is given to the merits and limitations of these methods when applied to industrial plants.

Instruments and Measurements

46-107—Parallel Circuits in Servomechanisms; *H. T. Marcy (A '42). 30 cents.* In a process controlled by a servomechanism, measurements are made of desired and of controlled quantities. Analytical techniques heretofore described by various authors become awkward to use

1. When the measurement of the error between desired and actual quantities is not very fast compared with the speed of response of the remaining system.

2. When there are components in the control system which employ feed-back circuits.

This paper describes the application to these problems of an analysis which uses the reciprocal of the usual system function. The reciprocal system function is defined as an operational expression of a nondimensional ratio of component input to component output.

46-114—The Frequency Response of Automatic Control Systems; *Herbert Harris, Jr. 30 cents.* This paper illustrates the advantages of the frequency response approach to the analysis of automatic control systems as contrasted to the analytic solution of transient response. At the same time the equivalence of information available from the two approaches is demonstrated. A numerical example is given based upon a torque amplifier using a motor-generator type control.

46-133—Functional Analysis of Measurements; *I. F. Kinnard (F '43). 30 cents.* This article shows the need for a practical method of systematically analyzing all types of measurement apparatus, and outlines such method actually in use. Specific new terms and definitions are suggested for various functional parts of measurement devices or systems, and other terms commonly used are defined carefully. A number of measurements performed by apparatus using electrical means are analyzed and illustrated, using the methods described. Statistical data on functional parts of measurement equipment are shown. The benefits that can be obtained from the application and general use of the proposed functional analysis and classification method are discussed.

46-135—A New Design for the A-C Network Analyzer; *J. D. Ryder (A '40), W. B. Boast (M '43). 20 cents.* In line with the increased interest in a-c network analyzers, the Iowa State College has been active in developing and constructing an analyzer for use by utilities of the Midwest area. A pilot model of the analyzer, to employ an operating frequency of 10,000 cycles per second, has been built and tested. Advantages obtained by the use of a high operating frequency are reduced instrument burden, reduced power levels, and the opportunity to avoid the use of iron cores in the reactor units. The latter feature provides a major improvement in accuracy. Lowered cost is shown as possible through the use of techniques and apparatus common to the electronic and radio fields.

46-142—High-Vacuum Leak Testing With the Mass Spectrometer; *W. G. Worcester (A '42), E. G. Doughty. 30 cents.* A simple mass spectrometer which will detect extremely small quantities of helium provides an excellent method for the detection and accurate location of leaks in vacuum systems. The instrument described offers high sensitivity and quick response and is capable of detecting a small leak in the presence of a large leak. Large or small systems of metal, glass, or other materials can be tested. Since the response is not affected by outgassing, it is not necessary to produce a high vacuum in the test piece. Testing time is short, and the system lends itself to production tests. The paper includes a discussion of the theory and design requirements of the leak detector, a description of the instrument, and a discussion of the applications of the method to large and small systems.

46-155—Frequency Compensated A-C Ammeters and Voltmeters; *J. M. Whittenton (A '37), C. A. Wilkinson. 15 cents.* A comprehensive discussion of the factors causing frequency errors in uncompensated type a-c moving-iron ammeters and voltmeters is covered in this paper. A general discussion is given to the practical methods of compensation which can be applied to standard instruments to reduce errors in calibration to negligible values when instruments are calibrated at one frequency and used over a range of 25 to 3,000 cycles. Results are tabulated to show the reduction of frequency errors in ammeters by the use of high permeability materials in proper combination in the magnetic circuit to reduce eddy current losses. The effectiveness of these improvements in combination with the proper shunting of a portion of the series resistors of the voltmeters with required values of capacitance to correct also for changes in inductive reactance is described, and the reduction in frequency errors is given.

Marine Transportation

46-127—Design of D-C Auxiliary Controllers for Marine Service; *W. Schaelchlin (M '45). 20 cents.* This paper briefly discusses the various problems involved in the design of control equipment for shipboard service. The effect the number of starting steps has on current surges, and the advantages and disadvantages of various means of automatic acceleration are described. Overload protection of continuously and intermittently rated motors is discussed in detail, and particular reference is made to the problem of protecting intermittent motors. Resistors for starting and speed regulating duty are considered an important controller component, and discussion of them includes a table with recommended resistor classes for the various applications. A number of points must be considered in the design of enclosures for dripproof or waterproof controllers. Strength, ventilation, condensation, and other such details are covered. The paper concludes with a discussion of various types of controller assemblies for deck and underdeck applications and contains illustrations of typical equipment.

46-149—Propulsion Control Problems With Diesel-Electric Synchronous Motor Ship Drives; *E. Frisch. 20 cents.* Although the many obvious advantages of ship propulsion drives with synchronous motors and generators and with power supplied by Diesel electric engines have been realized for some time, no actual installations were made in the United States until a few years ago. At that time a trial installation was completed on a 12,000 horsepower twin-screw vessel. Experience thus gained has established its superiority in many respects, and indications are that it may find extensive use on future vessels. The paper discusses control problems associated with the drive and describes methods of control and types of control equipment which have been found best suited for the drive.

Power Generation

46-108—Tennessee Valley Authority Hydroelectric Stations—Electrical and Mechanical Design; *R. A. Hopkins (F '43), H. J. Petersen. 25 cents.* Design policies have been developed and established during the building and operating of 14 major hydroelectric generating stations since 1934. Turbines, governors, generators, transformers, switchgear, and other major equipment have been selected generally in accordance with normal manufacturers' designs, except in specific cases where operating experience has indicated a definite

need for improvement. Many of the improvements have become standardized by the manufacturers. Switching, bussing, control, relaying, wiring, piping, auxiliary equipment, and other station features have been developed by the Authority, using manufacturers' standard components as far as possible. The bases for selection of equipment and for development of station designs undoubtedly are applicable to other hydro projects.

46-144—Improvements in Performance of Hydroelectric Generating Units on the 2,000,000-Horsepower Saguenay System; *F. L. Lawton (M '36). 25 cents.* The large number of high-capacity hydroelectric generating units in power plants of the Saguenay System, well-organized operating records, thorough engineering studies and experimentation, and foresighted management have made feasible important advances in efficiency and reliability of such units. Improved methods of operation have resulted in maximum energy output from storage water. Important criteria affecting rate of wastage of waterwheel-runner metal by pitting, and costs of repairs, are discussed. The significance of operating waterwheels at best gate, and means of accomplishing this by gate-position indicators, are noted. The effect of dirt on generator stator-winding temperature rise is developed. Improved generator performance from better application of stator-winding insulation, superior stranding and transposition of stator-winding coils, high-silicon stator iron, and better ventilation systems are discussed. Enhancement in waterwheel capacity and efficiency, effected through model and prototype performance tests, is noted.

46-152—Modern Excitation Systems for Large Synchronous Machines; *J. B. McClure (A '29), S. I. Whittlesey (A '45), M. E. Hartman. 20 cents.* This paper reviews the types of modern excitation systems that are now available for large synchronous machines. It includes a brief description of the complete excitation systems followed by a discussion of the modern types of exciters and regulators. The application guides indicate the present trends of excitation systems for the different types of synchronous machines. Co-ordinated excitation systems are now available for all types of application requirements, including existing installations. The automatic control features provided by modern voltage regulators make it possible to obtain improved system operation, to operate existing equipment at higher loadings, and to design more economical system extensions. Special motor-driven exciters may be used successfully in place of large high-speed shaft-driven exciters. Shaft-driven hydrogen-cooled exciters are available for moderate-speed synchronous machines.

46-154—The Development of Modern Excitation Systems for Synchronous Condensers and Generators; *F. M. Porter (M '45), J. H. Kinghorn (M '46). 25 cents.* This paper describes a development program for excitation systems of synchronous condensers and generators ranging in size from 5,000 to 36,000 kva. This improvement plan has been carried on over the past 15 years and includes 15 exciter applications which are located on the systems of the American Gas and Electric Company. Installations involving 5 electronic pilot exciters, 4 electronic main exciters, 14 electronic regulators, and 6 direct connected exciters with amplidyne control are covered. Descriptions of several typical arrangements with photographs and connection diagrams are given. Operating experience with this equipment is presented and discussed. Tables, including operating time and tube life for the nine electronic exciters, are given. The fine performance of the various excitation schemes is recounted and demonstrated. Definite conclusions are drawn by the authors as a result of many machine years of satisfactory performance obtained with these numerous modern excitation systems.

Power Transmission and Distribution

46-103—Determination of Cable Temperatures by Means of Reduced Scale Models; *Andrew Gemant, Joseph Stiehler (M '39). 25 cents.* A method, using reduced-scale model installations, is developed for the laboratory determination of cable temperatures obtaining in the field. The theory of the method is given, followed by the description of three sets of experiments conducted to show the feasibility of the method. One set of experiments is concerned with a single-conductor cable buried directly in the soil of the model setup, and temperatures obtained are compared with computed values. Another set is concerned with a single-conductor cable in a model duct bank, and sheath and duct temperatures obtained are compared with those of field determinations in an actual field installation. The third set is concerned with a model three-conductor cable in a duct bank, and conductor-sheath temperature differentials are compared with field data. All tests show that the accuracy of the method is sufficient for practical purposes.

46-115—F-3 Lead Alloy—An Improved Cable Sheathing; *L. F. Hickernell (F '34), C. J. Snyder. 20 cents.* Operating requirements for the lead sheath of modern impregnated-paper insulated power cable are outlined. The properties of present sheathing materials are reviewed, and the deficiencies pointed out. To meet present requirements, an extensive development program was undertaken and the material evaluated by a large utility. The best results were obtained with a new sheathing material composed of small amounts of arsenic, tin and bismuth, and remainder lead, known as F-3 alloy. Tests have shown that this material has unusual endurance or fatigue resistance under both dynamic and static loading. Outstanding properties are its resistance to bending fatigue, creep, and cracking under long-time static loading. It will not harden with age. F-3 alloy can be applied to cables by available manufacturing equipment. Also, it can be used for joint sleeves. Commercial lengths have been produced and installed on utility systems.

46-117—The Electrical Performance of Ceramic Dielectrics at Elevated Temperatures; *H. A. Frey (M '43), J. A. Jenzko (A '41). 30 cents.* Some recent developments have emphasized the need for information concerning the temperature at which dielectrics can be operated without electrical breakdown. This paper deals primarily with porcelain, but some data are included on the performance of steatite, glass, and zircon compositions. Data are presented on the variation in resistivity of the materials with varying temperature and also with varying voltage gradient. From the temperature–resistivity curves a method is developed for approximating the combination of temperature and voltage gradient which will result in electrical failure. Supporting data in the form of breakdown tests made at various temperatures are included. These tests include practical insulator forms as well as prepared test specimens.

46-118—Semiconducting Shielding for A-C Power Cable; *E. J. Merrell (A '41). 15 cents.* Graphs showing the electrical properties of semiconducting shields for a-c power cable are presented, together with background theory, illustrative problems, and experimental verification. The theory is based upon an adaptation of the exact hyperbolic formulas for a-c transmission lines to the circuit conditions represented by a cable dielectric and its semiconducting covering. Formulas and co-ordinates have been expressed in conventional electrical engineering terms, so that the theory and graphs may find ready application to cable measurements and design. All probable cable constants are covered by the graphs, specific solutions being obtainable by interpolation.

46-121—High-Voltage D-C Testing of Rubber-Insulated Wire; *W. N. Eddy (F '40), W. D. Fenn (M '44). 15 cents.* At different stages in the manufacture of insulated wire and cable, various electrical and physical tests are made to ensure the quality and serviceability of the completed cable. One of the most important of these tests is the high voltage test—alternating or direct current. It may be applied to short sections of the insulated conductor as it passes through electrodes of various types, dry or wet, or to full factory lengths of the insulated wire, dry or wet. The scope of this paper is limited to the results of an experimental study made on the voltage limits suitable for the high voltage d-c testing of factory lengths of plain insulated wire immersed in water. In addition to many sample tests, the study included tests on more than 5,500 different factory lengths of submarine cable conductor, insulated with natural rubber, synthetic rubber, or polyethylene. Such factors as testing volt-

age, type of fault, and immersion time were varied over a wide range. From these data test voltage limits are suggested; the lowest test voltage that will indicate serious defects, and the highest test voltage that can be used without causing damage to sound insulation, from either the d-c test voltage itself or from impulse voltages incidental to the testing.

46-125—The Preservative Treatment of Various Species Proposed for Poles and Crossarms; *J. D. MacLean. 15 cents.* The unprecedented drain on the nation's supply of poles imposed by the war needs and the backlog of pole requirements that has been built up, coupled with the reduced supply of creosote, have resulted in an acute shortage of treated poles and crossarms. The results of research by the Forest Products Laboratory during the past three decades have been reviewed, and recommendations are made in this paper for the use of alternate species, including spruce, Eastern white pine, Douglas fir, and 11 other species. Although creosote is recognized as the leading preservative, the chlorinated phenols and the creosote solutions provide suitable protection when necessary penetrations are obtained. The pressure method of treatment is the most satisfactory because it affords a means of controlling the absorptions, but nonpressure methods may be used successfully. Minimum net retentions of 4 to 8 pounds per cubic foot are specified for the pressure treatment of poles. The treating conditions and specifications for pressure treatment are given for the 14 alternate species for poles and crossarms.

46-160—Moisture Equilibrium Between Gas Space and Fibrous Materials in Enclosed Electric Equipment; *J. D. Piper. 20 cents.* In enclosed equipment, such as gas-filled transformers, the moisture concentration in the gas space reaches equilibrium with that in any fibrous materials present. The resulting vapor pressure is a function of the constitution, moisture concentration, and temperature of the fibers, but, at least for paraffin-impregnated cotton, is independent of whether or not the fibers are impregnated. A chart, prepared from published literature, shows the equilibrium vapor pressures for cotton having moisture concentrations from 0.01 to 10 per cent by weight for temperatures from 10 to 110 degrees centigrade. By multiplying the moisture concentrations by 1.7, the same chart is approximately applicable for kraft paper. Agreement between the chart and experimental data for paraffin-impregnated cotton is shown. Practical uses of the chart include nondestructive estimation of moisture concentrations in fibrous materials from the temperature of the fibers and the dew point of the gas.

46-175—Co-ordination of Insulation and Spacing of Transmission-Line Conductors; *W. W. Lewis (F '38). 15 cents.* The following criteria are suggested as a basis for the selection of minimum line insulation: The 60-cycle wet flashover must equal or exceed the voltages expected from faults and switching surges; the impulse flashover should equal or exceed the standard basic impulse insulation level for the terminal equipment. With each level of insulation there is a proper spacing between conductors and to the steel structure to develop the full strength of the insulator string selected. It is proposed that the minimum spacing A to the steel structure have an impulse flashover ten per cent greater than the flashover of the insulator string. Then the horizontal spacing from conductor to tower when conductor is hanging vertical will be $1.5A$, spacing between conductors in vertical arrangement will be $2A$ and in horizontal arrangement $3A$, and height of ground wires above top conductors will be $2A$.

46-176—Six-Years' Experience With Factory-Built Unit Type Substations; *E. F. Miller (M '44), R. B. Miller (A '36). 15 cents.* This paper outlines six years of operating experience with factory-built unit type substations and their application in a 4-kv primary network. The results obtained with the use of bus regulation, where it has been substituted for individual induction feeder voltage regulators, are outlined, as are also operating and maintenance experience with this type of equipment. History of the distribution system in which these substations are used is outlined, and reasons for the selection of the primary network type of distribution system and the selection of factory-built unit type substations are given.

Protective Devices

46-109—Fault Location and Relay Performance Analysis by Automatic Oscillographs; *H. P. Dupuis (A '41), W. E. Jacobs (A '44). 15 cents.* The method for determining the location of ground faults described in this paper is independent of generation, fault resistance, or the type of ground fault. This method applies particularly to faults in a network of two or more parallel lines and is based on a comparison of the magnitude and direction of ground currents in the faulted and unfaulted circuits. The paper describes the procedure in making ground current and ratio curves, and illustrates their application in locating faults and in determining critical conditions for relay selectivity. The summary classifies the type and cause of 256 line faults analyzed over a period of 5 years.

46-134—Application Ratings of Indoor Power Circuit Breakers; *O. B. Vikoren (M '43). 20 cents.* Increased cost involved in serving electric power to customers and the aim to lower rates have accelerated the need for most efficient utilization of existing generating and distribution equipment. This paper describes a method for loading power circuit breakers on a temperature basis for the purpose of taking advantage of their inherent current carrying ability. Several years of practical application of the basic theory have proved entirely satisfactory on various types of electric equipment and have in many cases established considerable savings on new investments. While these savings are less applicable to circuit breakers than to other major power equipment, their application in accordance with temperature, rather than name plate rating, has put the use of new and existing facilities on an equally sound engineering basis.

46-168—Low-Current Secondary Current Transformers; *AIEE subcommittee report. 15 cents.* This paper is a report of a working group of the relay subcommittee, covering the use of current transformers having secondary current ratings less than the generally accepted 5-ampere standard. Applications requiring low secondary current ratings are considered along with the advantages and disadvantages resulting from the use of such transformers. Consideration has been given to the availability of equipment, such as meters, instruments, and relays, suitable for use with low-current secondary currents, as well as some of the problems involved in designing equipment for this service. Where applications require the use of low secondary currents, solutions are suggested using standard meters, instruments, or relays employing auxiliary current transformers.

46-169—Protection of Powerhouse Auxiliaries; *AIEE subcommittee report. 20 cents.* The AIEE relay subcommittee has reviewed the protection of generating station auxiliary power motors to obtain information on auxiliary power systems now in use and the protective methods being applied, and to make recommendations on preferred practices. The paper includes a number of answers to a questionnaire covering data on supply systems used, various forms of protection applied, and a summary of the experience obtained with these systems. The practices and experiences of several major companies are summarized, and preferred practices are recommended based on this experience.

46-170—Performance Criteria for Current Limiting Power Fuses—I; *C. L. Schuck (A '39). 20 cents.* This paper describes empirical results of changes in test circuit variables on the interrupting performance of current limiting power fuses. The influence of generated voltage, available current, fault starting angle, fuse operating time, frequency, power factor, and the number of phases, are appraised for their effect on the severity of test conditions. Reference is made to Part II of the paper, in which the analytical framework is developed, for the necessary generalizations and extensions of the empirical data. Oscillograms of fuse interruption tests made in a short-circuit testing laboratory are presented to illustrate differences in test severity. Based on these observations, recommendations are made for test procedures and conditions for establishing the interrupting ratings of current limiting power fuses.

46-171—Performance Criteria for Current Limiting Power Fuses—II; *E. W. Boehne* (*F '43*). *30 cents.* This paper presents a graphical, analytical study of the effect of the circuit variables upon the performance of power fuses. The magnitude of the arc voltages and the time of their introduction following the short circuit are chosen to favor the performance characteristic of power fuses of the current limiting type. The analytical methods employed, however, as well as the general equations of arc energy and conductor heating presented in the paper, are applicable to the general fuse problem, but particularly adapted to the analysis of fuse performance operating in low power factor single-phase circuits. Some of the more interesting results of this work are confirmed by oscillograms which are discussed in paper 170. It is shown, for example, that maximum energy liberated by the power fuse is dependent upon the fault starting angle and is not associated necessarily with the maximum interrupting rating of the fuse. The effect of circuit frequency upon the fuse performance is particularly interesting.

46-172—Philosophy of Relaying; *E. W. Knapp* (*M '44*), *Ben C. Hicks* (*M '45*). *20 cents.* Philosophically the electric power system exists to serve certain human needs, and it must serve them better and more economically than they could be served by other methods, or it would not be able to continue to exist or to grow. The rendering of service of the required degree of excellence, within economic limitations, is not an inherent attribute of the electric power system but is the result of sustained and carefully co-ordinated effort on the part of all concerned in the rendering of the service, including:

1. Precautions taken in the design of equipment to make it trouble free and reliable.

2. Precautions taken in system layout and connections to enable service to be rendered continuously under adverse as well as under favorable conditions.

3. Precautions taken in the operation and maintenance of the system to avoid unnecessary interruptions to service.

46-173—Simplicity in Protective Relaying; *L. F. Hunt* (*F '38*). *20 cents.* Simplicity relay circuits and the importance of ground relaying are pointed out in this paper. Protection engineers have outgrown the small job of studying the behavior of relays. Their major task is to give customers of electric energy good continued service from an over-all system viewpoint by seeing that the least amount of equipment be tripped to isolate faulty sections. It is their duty to assist in over-all station and system designs that can be adapted for the ultimate of service with structures having the smallest hazards to faults. Many of the relay systems for transmision, distribution, and equipment are described that have given almost perfect operation on the entire system of the Southern California Edison Company, Ltd.

Safety

46-112—Dangerous Electric Currents; *C. F. Dalziel* (*M '30*). *20 cents.* This paper discusses lethal electric currents and their accompanying physiological effects, and interprets the data of a former AIEE paper, "Effect of Electric Shock on the Heart," by L. P. Ferris, B. G. King, P. W. Spence, and H. B. Williams, in accordance with an original method of analysis found useful by the author in his own investigations of "let-go" currents. The present analysis concerns itself with threshold currents likely to produce instantaneous electrocution in one half per cent of a large group of normal men. Although the conclusions are derived from tests made on animals, it is believed that the results may be indicative of what might be expected to occur in man. The majority of the work is based on experiments made at 60 cycles with shock durations of 0.03 to 3.0 seconds. Predictions of lethal currents for both direct current and condenser discharges, while more speculative due to the limited data available, are included because of their importance due to the greatly increased use of d-c and electronic equipment. Dangerous effects at high frequencies also are mentioned.

46-159—ACO—Silent, Invisible Industrial Hazard; *S. Reid Warren, Jr.* (*M '41*). *20 cents.* The use of X rays or gamma rays in industry is increasing. Adequate protection of personnel from harmful effects of these radiations is of paramount importance, particularly because these effects may not be evident until several months or years after exposure to radiation. This paper describes briefly some of the properties of X rays and gamma rays, the harmful effects that they may produce in human beings, and the principles upon which the design of adequate protection depends.

PERSONAL ....

L. R. Brown (M '24) formerly manager of the transformer division, General Electric Company, Pittsfield, Mass., has been advanced to the staff of the manager of the company's central station divisions. Mr. Brown was graduated from the University of Wisconsin in 1903 and that year entered the employ of the company. Mr. Brown was made manager of distribution transformer sales in 1910 and manager of the entire transformer division in 1923. **H. F. McRell** (A '25) formerly assistant manager of the distribution transformer division, General Electric Company, Pittsfield, Mass., has become division manager. Mr. McRell joined the company in 1910 in Schenectady and in 1913 was transferred to Pittsfield to the transformer division. He has been senior transformer engineer in New York, St. Louis, Mo., and Chicago, Ill. In 1924 he was made sales manager of the distribution transformer section and in 1942 assistant manager of the transformer division. **P. M. Staehle** (A '17) formerly sales manager of the specialty transformer section, General Electric Company, Fort Wayne, Ind., becomes manager of the newly formed specialty transformer division. A graduate of the University of Wisconsin, Mr. Staehle entered the employ of the company in 1912 in Schenectady. In 1913 he was transferred to the transformer engineering department at Pittsfield and to Fort Wayne in 1916. After a period, from 1924 to 1929, as Mr. McRell's assistant, he returned to Fort Wayne as manager of sales.

William McClellan (A '04, F '12) chairman of the board, Union Electric Company, St. Louis, Mo., has retired. Doctor McClellan, a past president of AIEE, holds the degrees of bachelor of science (1900), doctor of philosophy (1903), and electrical engineer (1914) from the University of Pennsylvania. Before 1907 he was associated with the Philadelphia (Pa.) Rapid Transit Company and Westinghouse, Church, Kerr and Company, New York, N. Y. Throughout his career he was partner in a number of engineering firms—Campion, McClelland Company, 1907–15; Paine, McClelland, and Campion, 1915–20; McClelland and Junkersfeld, 1922–29; William McClelland and Company, Ltd., 1930–33. Executive for many firms he was vice-president of the Cleveland Illuminating Company from 1919 to 1921 and of Stone and Webster Engineering Corporation from 1929 to 1933, and president of the Potomac Electric Power Company from 1933 to 1939, of the Washington Railway and Electric Company and from 1935 to 1940, and of the Union Electric Company since 1939. He has served as director to other public utility firms. He is a member of the American Society of Mechanical Engineers, the Newcomen Society, the American Association for the Advancement of Science, and the American Academy of Political and Social Science. He also is a member of Phi Beta Kappa and Sigma Xi.

O. L. LeFever (A '10, F '44) formerly general superintendent, Northwestern Electric Company, Portland, Oreg., has been appointed chief engineer of the company. Mr. LeFever was graduated from Iowa State College in 1906 and spent one year with each of the following companies: the Minneapolis (Minn.) General Electric Company; the Twin City Rapid Transit Company, St. Paul, Minn.; the Northwestern Bell Telephone Company, Minneapolis; the Western Electric Company, Chicago, Ill.; and the Portland Railway, Light and Power Company. In 1913 he joined the Northwestern Electric Company as general foreman of underground construction. He successively became superintendent of steam distribution and general superintendent. **Tom Perry** (A '21) formerly assistant general superintendent of the plant department succeeds Mr. LeFever as general superintendent. Mr. Perry joined the Northwestern company as assistant superintendent of Portland stations in 1919.

A. L. Samuel (M'34) formerly electronic research engineer, Bell Telephone Laboratories, Inc., New York, N. Y., has been appointed professor of electrical engineering at the University of Illinois, Urbana. Doctor Samuel received the degree of bachelor of arts from the College of Emporia in 1923, and the bachelor of science degree in 1925 and master of science degree in 1926 from Massachusetts Institute of Technology. Recently he was awarded the honorary degree of doctor of science by the College of Emporia. After two years, from 1925 to 1927, as instructor of electrical engineering at Massachusetts Institute of Technology, Cambridge, Doctor Samuel became a member of the technical staff of Bell Laboratories. He has been active in the development of gas rectifiers, thyratrons, and vacuum tubes for use at ultrahigh frequencies and has many technical papers and patents to his credit. He is a member of the American Physical Society, the American Association for the Advancement of Science, and the Institute of Radio Engineers.

Theodore Braaten (A '22, M '31) formerly lieutenant colonel, United States Army, has been appointed general manager of the Gas and Electric Department of Norwich, Conn. After his graduation from the Massachusetts Institute of Technology, Cambridge, in 1920, Mr. Braaten taught there for one year and then spent a year investigating hydroelectric facilities in Norway. Later he was connected with the Public Service Company of Northern Illinois, the Westinghouse Electric Corporation, East Pittsburgh, Pa., and Boston Mass., and the Boston Edison Company. Having served as a lieutenant of field artillery in World War I, he entered the Army in 1942 as a captain. Overseas he was assigned to Supreme Headquarters of the Allied Expeditionary Forces and was responsible for restoration of public utilities in Holland and Germany. Later he was titled chief of public utilities, SHAEF Mission, Norway.

Bernard Hague (M '30) formerly lecturer on electrical engineering, University of Glasgow, Scotland, has been appointed to the James Watt Chair of Electrical Engineering at the University of Glasgow. Doctor Hague holds the degrees of bachelor of science (1913), master of science (1919) and doctor of science (1927) from the University of London and the doctor of philosophy degree (1926) from the University of Glasgow. In 1916 he became a technical assistant in the physics research department of the Royal Aircraft Establishment, Farnborough, and relinquished this position to become a lecturer at the City and Guilds College, London, in 1920. He joined the faculty of the University of Glasgow in 1923 as lecturer in electrical engineering. In 1929 and 1930 he was visiting professor at the Polytechnic Institute of Brooklyn, New York, N. Y. Doctor Hague has published a number of books and many technical articles.

J. W. Sheffer (A '10, M '13) formerly general electrical engineer, improvement department, American Car and Foundry Company, New York, N. Y., has been appointed general improvement engineer. Mr. Sheffer holds the degrees of mechanical engineer (1907) from Cornell University and master of arts (1933) from Columbia University. He joined the company in 1908 at Berwick, Pa., where he successively was electrical engineer and assistant to the general superintendent and plant engineer. In 1926 he was transferred to New York where he has been occupied with improvement and development problems. He is a member of the American Welding Society and the Association of Iron and Steel Engineers. **H. F. Schwarting** (A '16, M '21) formerly field engineer, improvement department, has been appointed general electrical engineer with headquarters in St. Louis, Mo.

J. F. Calvert (A '27, F '45) chairman of electrical engineering department, Northwestern Technological Institute, Evanston, Ill., has received a letter of commendation from the United States Navy for planning and directing construction of the Pearl Harbor demagnetization station at which warships were treated electrically for protection against mines. The letter praised Professor Calvert as follows: "Through your devotion to duty, tireless effort, and acceptance of personal risk during and following the attack on Pearl Harbor, this station was completed by the summer of 1942, and remains the finest in all of the Pacific ocean areas. May it continue to serve . . . . as a constant testimonial to your exceptional engineering accomplishments."

H. L. Rusch (A '24) formerly executive vice-president, A. C. Nielsen Company, Chicago, Ill., now is associated with the Public Opinion Index for Industry, a division of the Opinion Research Corporation, Princeton, N. J. Mr. Rusch was graduated from the University of Wisconsin in 1923 and, after a four-year association with the Nielsen company, joined the Johns-Manville Corporation, New York, N. Y., in 1928 as supervisor of its technical data and performance report section. In 1933 he was made vice-president and Eastern manager of the Northern Pump Company, New York, N. Y. He rejoined the Nielsen company in 1937 and in 1938 was elected vice-president.

A. W. Ray (A '19, M '45) manager of the service department, Reliance Electric and Engineering Company, Cleveland, Ohio, has retired. Mr. Ray was born in Rockport, Ohio, and attended Ohio State University. The second employee to be hired by the Reliance company when it was organized in 1905, Mr. Ray has been design draftsman, chief draftsman, acting chief engineer, and senior design engineer. He was appointed manager of the service department in 1923.

G. E. Sangster (A '43) recently lieutenant in the United States Naval Reserve, has been appointed sales development engineer by Sangamo Electric Company. He is a graduate of both Benjamin Franklin University and George Washington University and previously was valuation engineer with the Potomac Electric Power Company, Washington, D. C.

F. B. Powers (M '37) overseas traction manager, Westinghouse Electric International Company, New York, N. Y., has resigned to become vice-president in charge of operations and engineering of all divisions of Great American Industries. Mr. Powers will supervise production activities of the Connecticut Telephone and Electric division, Meriden, Conn.; Virginia Rubatex division, Bedford, Va.; the Rex division, New Rochelle, N. Y.; the War LaFrance division, Elmira, N. Y.; and the Rutland, Vt., division.

Albert Preisman (M '41) formerly director of engineering texts and consulting engineer, Capitol Radio Engineering Institute, Washington, D. C., has been appointed vice-president in charge of engineering. Mr. Preisman, who holds the bachelor of arts and electrical engineering degrees from Columbia University, has been with the Radio Engineering institute since 1943. Previously he was senior engineer with Federal Telephone and Radio Corporation.

W. R. Hutchins (A '42) who for the past several years has been associated with Major Edwin H. Armstrong in research and development work on frequency modulation and radar at Columbia University, New York, N. Y., and in Alpine, N. J., has been appointed manager of frequency modulation broadcasting activities of E. Anthony and Sons, New Bedford, Mass.

I. C. Eppley (A '43) formerly supervisor of electrical engineering, Dayton (Ohio) Power and Light Company, has been made assistant manager of the electrical engineering division. Mr. Eppley joined the company in 1924 as assistant electrical engineer. **H. E. Deardorff** (A '37) formerly supervisor, system planning engineering, is now manager of the electrical planning department.

F. E. Baker (A '40) formerly section engineer in the distribution transformer engineering division, Westinghouse Electric Corporation, Sharon, Pa., has been appointed section engineering manager in the newly created specialty transformer department at Sharon. Mr. Baker joined the Westinghouse corporation as design engineer after his graduation from Bucknell University in 1925. He became section engineer in 1940.

E. M. Haacke (A '45) formerly associate editor of *Electrical News and Engineering*, Toronto, Ontario, Canada, has been appointed editor. Mr. Haacke was graduated

from Queens University in 1942, and from 1942 to 1944 served as navigator and radar officer in the Royal Canadian Air Force. He joined the staff of *Electrical News* in 1945.

M. W. Locke (M '44) chief engineer of the Powerton station of the Commonwealth Edison Company, Chicago, Ill., has been appointed superintendent of the superpower department. He will continue in his present position and in addition have charge of the transmission and construction division of the superpower department.

J. W. Pomazal (A '40) formerly engineer in the engineering department, Kurz and Root Company, Appleton, Wis., has been named sales engineer in charge of all sales activities. Mr. Pomazal, who joined the company in 1945, previously was associated with Louis-Allis Company, Milwaukee, Wis. He is a member of the Engineers Society of Milwaukee.

R. H. Porterfield (A '44) resident field engineer, Allis-Chalmers Electrical Manufacturing Company, Providence, R. I., has been appointed manager of a new branch office of the company in Providence. Mr. Porterfield, who has been with the Allis-Chalmers company since 1939, is a graduate of the University of Nebraska.

Joseph Slepian (A '17, F '27) associate director of research, research laboratories, Westinghouse Electric Corporation, East Pittsburgh, Pa., recently received a 1945 fellow award of the Institute of Radio Engineers "in recognition of his contributions as scientist, engineer, and inventer to the field of electronics."

C. W. Hansell (A '23, M '44) research supervisor, transmission, RCA Laboratories, Radio Corporation of America, Rocky Point, N. Y., recently received a 1945 fellow award of the Institute of Radio Engineers "for his pioneer work in the development and application of equipment for the ever higher frequencies employed for radio communication."

A. L. Samuel (A '34) electronic research engineer, Bell Telephone Laboratories, Inc., New York, N. Y., recently received a 1945 fellow award of the Institute of Radio Engineers "for his fundamental work in the field of electronic research and for development of electronic devices of particular value at very high frequencies."

F. J. Given (A '28) engineer, apparatus development department, Bell Telephone Laboratories, Inc., New York, N. Y., has assumed the additional duties of transmission apparatus engineer and as such will have charge of work on transmission transformers and power apparatus.

J. D. Lawrence (A '25) formerly district manager, Logan, W. Va., has been appointed assistant division manager of the Roanoke division of the Appalachian Electric Power Company, Roanoke, Va. Mr. Lawrence, who has been with the company since 1923, has been district manager at Logan since 1943.

J. J. Conners (A '40) formerly general sales manager, Irvington (N. J.) Varnish and Insulator Company, has been appointed vice-president and sales manager of the Bishop Gutta Percha Company, New York, N. Y., and the Peters Manufacturing Company, Wollaston, Mass.

R. W. Raine (A '42) formerly manager of the electrical design department, Robert and Company, Eglin Field, Fla., has joined the firm of Edward D. de Luca and Associates, consulting engineers, Jacksonville, Fla., as head of the electrical design department.

L. E. Hildebrand (M '21) formerly electrical engineer, General Electric Company, Lynn, Mass., has been appointed assistant designing engineer of the motor engineering division. Mr. Hildebrand has been with the company at Pittsfield and Lynn, Mass., since 1913. He is a graduate of Oklahoma Agricultural and Mechanical College.

J. M. Evans (A '20, M '28) electrical engineer with the United States Army Engineers, San Francisco, Calif., has been named supervising electrical and mechanical engineer for the Navy Bureau of Yards and Docks and as such will have supervision over installations in the 11th and 12th Districts which comprise California, Nevada, and Utah.

H. E. Hill (A '31) formerly lieutenant colonel, United States Army, has returned to Bell Telephone Laboratories, Inc., New York, N. Y. Colonel Hill at various times was stationed in Aberdeen, Md., Fort Bliss, Tex., Hawaii, and at the headquarters of the Central Pacific Base Command.

A. C. Schwager (A '24, F '44) formerly vice-president and chief engineer of the Pacific Electric Manufacturing Corporation, San Francisco, Calif., has accepted the position of president of the Schwager-Wood Corporation, Portland, Oreg., specializing in the manufacture of high voltage airbreak switches.

A. B. Paterson (M '22) president, New Orleans (La.) Public Service Company, has been awarded the New Orleans Times-Picayune loving cup "in recognition of his 15-year record of civic services" to his community.

L. B. Potter (A '45) formerly field engineer, The Detroit (Mich.) Edison Company, has been appointed utilization equipment and primary supply engineer of system engineering. Mr. Potter entered the employ of the company in 1928.

R. P. Lapsley (A '38, M '45) lieutenant colonel, United States Army Engineers, has been presented with the Legion of Merit for his outstanding performance of services as chief, Electrical and Utilities Service Section, Engineering Division, of the South Atlantic Division.

James Bisset (A '28) assistant superintendent of the meter bureau, Consolidated Edison Company of New York, Inc., Flushing, N. Y., has retired. Mr. Bisset had been with the company since 1910.

N. B. Phillips (M '34) formerly superintendent of the testing laboratory and services, Buffalo (N. Y.), Niagara Electric Corporation, has been appointed superintendent of the meter department. Mr. Phillips joined the company in 1909.

W. R. Le Page (A '34, M '44) formerly assistant director, radiation laboratory, Johns Hopkins University, Baltimore, Md., is now senior research engineer, Stromberg-Carlson Company, Rochester, N. Y.

C. G. Suits (M '41) vice-president and director of research laboratory, General Electric Company, Schenectady, N. Y., has been elected a member of the National Academy of Sciences.

W. J. Gilson (A '26, M '38) general manager, Eastern Power Devices, Ltd., Toronto, Ontario, Canada, has been appointed vice-chairman of the Canadian Council of Professional Engineers and Scientists.

W. R. Harmer (A '37, M '44) supervising industrial engineer, sales promotion department, Hydro-Electric Power Commission of Ontario, Toronto, Canada, has been elected secretary of the Association of Municipal Electrical Utilities.

H. G. Sherlock (A '39) formerly equipment engineer, Mountain States Telephone and Telegraph Company, Denver, Colo., has been appointed equipment and building engineer. Mr. Sherlock joined the company in 1926.

J. E. Lawson (A '22) vice-president and general manager, executive department, Canadian Niagara Power Company, Ltd., Niagara Falls, Ontario, has been elected a director of the company.

G. R. Mezger (A '37) formerly commander in the United States Navy, has rejoined the Allen B. DuMont Laboratories, Inc., Passaic, N. J., as manager of instrument sales. He entered the Navy in 1941 as lieutenant, junior grade.

R. G. McCurdy (A '16, F '34) director of electric apparatus development, Bell Telephone Laboratories, Inc., New York, N. Y., has added the supervision of groups on electrical measurements and magnetic studies and applications to his duties.

K. T. Compton (F '31) president, Massachusetts Institute of Technology, Cambridge, recently was awarded the Medal of Merit "for outstanding services to his country" in the development of microwave radar.

F. D. Newbury (A '07, F '21) vice-president of Westinghouse Electric Corporation, Pittsburgh, Pa., has been elected a member of the board of directors of the company.

F. E. Terman (A '23, F '45) dean of engineering, Stanford University, Stanford University, Calif., recently was elected to the National Academy of Sciences.

G. C. Hyde (A '11) president, Louisiana Public Utilities Company, Inc., Dallas, Tex., has been elected president of the Gulf Public Service Company, Inc., New Iberia, La.

N. R. Gibson (M '32) vice-president, Buffalo (N. Y.), Niagara, and Eastern Power Corporation, has been elected a director of the Canadian Niagara Power Company, Ltd.

Hugh Jack (A '21) chief of the a-c engineering department, British Thomson-Houston Company, Ltd., Rugby, England, has become a director of the company.

Vannevar Bush (A '15, HM '45) director of the Office of Scientific Research and Development, and president of the Carnegie Institution, Washington, D. C., recently was awarded the Public Welfare Medal of the National Academy of Sciences.

A. A. Schuhler (A '19, M '27) formerly commercial engineer, Federal Telephone and Radio Corporation, Newark, N. J., has been appointed New York (N. Y.) branch manager, Stanley and Patterson division, Faraday Electric Corporation.

F. D. Newbury (A '07, F '21) vice-president, Westinghouse Electric Corporation, Pittsburgh, Pa., has been elected a member of the company's board of directors.

F. E. Harrell (A '26, F '40) general works manager, The Reliance Electric and Engineering Company, Cleveland, Ohio, has been elected a member of the board of directors of the company.

A. C. Streamer (A '10, M '41) vice-president, Westinghouse Electric Corporation, Pittsburgh, Pa., recently was awarded the honorary degree of doctor of engineering, by the University of Colorado from which he was graduated in 1907.

Rufus Moses (A '28, M '42) formerly division manager of the Pennsylvania Power Company, Sharon, is now Youngstown division manager for the Ohio Edison Company. Mr. Moses had been with the Pennsylvania company since 1926.

F. M. Oglee (A '41) formerly Philadelphia (Pa.) district manager, Trumbull Electric Manufacturing Company, has been appointed manager of sales in the company's Norwood, Ohio, plant. Mr. Oglee has been with the company since 1929.

B. F. Campbell (A '30) recently lieutenant commander in the United States Navy, has returned to the Philadelphia (Pa.) office of the Rumsey Electric Company as substation and transmission engineer.

C. S. Redding (A '12, M '41) president, Leeds and Northrup Company, Philadelphia, Pa., has been elected a director of the Philadelphia Electric Company. He is also president of the Franklin Institute.

H. B. Bryans (M '17, F '18) executive vice-president of the Philadelphia (Pa.) Electric Company, recently was elected president of the Electrical Association of Philadelphia.

J. F. Gogins (A '40) manager, apparatus department, General Electric Company, Spokane, Wash., has been elected to the executive committee of the Spokane Chamber of Commerce.

E. W. Loomis (A '19) district manager, Westinghouse Electric Corporation, Philadelphia, Pa., has been elected vice-president of the Philadelphia Electric Association.

W. K. Scott (A '42, M '44) formerly assistant chief electrician, Columbia Steel Company, Pittsburg, Calif., has been appointed electrical supervisor of new construction.

F. A. Lewis (M '35) vice-president, Hooton Chocolate Company, Newark, N. J., has been elected a director of the company.

S. R. Inch (A '04, F '38) formerly president of Ebasco Services, Inc., New York, N. Y., is now vice-chairman of the company.

J. I. West (A '26) district manager, Litchfield (Conn.) Electric Light and Power Company, since 1923, has resigned.

OBITUARY • • • •

Frank Alfred Wolff (A '99, M '34) retired principal telephone engineer, National Bureau of Standards, Washington, D. C., died March 28, 1946. Doctor Wolff, who was born April 8, 1871, in Baltimore, Md., received the degrees of bachelor of arts in 1890 and doctor of philosophy in 1893 from Johns Hopkins University. Following that he spent a year studying at the University of Leipzig in Germany. In 1894 he joined the Bureau of Soils of the Department of Agriculture in Washington as expert physicist. He first became associated with the Office of Standard Weights and Measures, later the Bureau of Standards, in 1897 as a verifier. From 1894 to 1898 he also was professor of physics and electrical engineering at Columbia University. Doctor Wolff successively was associate physicist, physicist, and senior physicist, and in 1915 became chief of the telephone section. In 1938 he was titled principal telephone engineer, and in 1941 he retired. He was concerned particularly with the establishment of the present system of international electrical units and published many technical papers. He was detailed to the Federal Communications Commission from 1935 to 1937. Doctor Wolff was an expert on valuation of currency and in this connection appeared several times as a witness in Senate hearings. He was a member of the AIEE committee on communication from 1918 to 1941.

Walter C. Dixon (M '36) of the engineering department of the Central New York Power Corporation, Syracuse, died February 28, 1946. Mr. Dixon was born in Warner, N. Y., June 24, 1887, and was graduated from Syracuse University in 1909. His first position was that of draftsman for the Gould Coupler Company, Depew, N. Y. Except for a period in 1914 and 1915 during which he was employed by the Duquesne Light Company, Pittsburgh, Pa., on the design of substations, he was associated with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., from 1912 to 1934. He was in the switchboard engineering department until in 1922 he was transferred to the general engineering department. In 1926 he was stationed in St. Louis, Mo., as general engineer for the company. He became utilities engineer in the Department of Public Utilities of the City of Memphis, Tenn., in 1934 and was transferred to the Memphis Light and Water Division in 1936. Mr. Dixon entered the engineering department of the Central New York Corporation in 1937.

Byron W. St. Clair (A '17, M '24) president and treasurer, Mico Instrument Company, Cambridge, Mass., died April 4, 1946. Mr. St. Clair was born March 14, 1892, and commenced his career in the meter department of the Louisville (Ky.) Gas and Electric Company in 1911. He changed position in 1912 to become tester and laboratory assistant with the General Electric Company, West Lynn, Mass., remaining there until he was commissioned ensign in the United States Naval Reserve in 1918. Upon his return to the General Electric Company in 1919 he was made engineer in charge of the standardizing laboratory and held this position until 1937. He was appointed president of the Mico Instrument Company in 1937 and treasurer in 1944. He formerly served on the AIEE committee on instruments and measurements.

Samuel Charles Margolin (A '32) assistant electrical engineer, Board of Transportation, City of New York, N. Y., died January 3, 1946. Born February 5, 1903, in Russia, Mr. Margolin was graduated from the College of the City of New York with the degree of bachelor of science in 1923. In 1924 he received the degree of electrical engineer from the Polytechnic Institute of Brooklyn. After a year as laboratory assistant for the Freed-Eismann Corporation, New York, he became junior draftsman with the Board of Transportation in 1926. He was made junior electrical engineer in 1927 and assistant electrical engineer in 1930.

Harry Lee Thomson (A '21) meter and appliance engineer, Hartford (Conn.) Electric Light Company, died March 24, 1946. Mr. Thomson was born February 17,

1887, in Thomson, N. Y. He finished a special electrical course at Renaselaer Polytechnic Institute in 1907 and the college course at the General Electric Company, Lynn, Mass., in 1910. He became assistant to the superintendent of lighting for the Hartford company in 1910 and superintendent of lighting in 1918. In 1933 he was appointed meter and appliance engineer. He was active on technical committees of the Edison Electric Institute and the Association of Edison Illuminating Companies, and on the AIEE committee on instruments and measurements from 1931 to 1942.

Mathias W. F. Zimmermann (M '43) electrical designer, Calco Chemical Division, American Cyanamid Company, Bound Brook, N. J., died March 23, 1946. Mr. Zimmermann, who was born June 17, 1910, in Weehawken, N. J., studied at Rutgers University. He was electrical draftsman in the plant engineering department of the General Cable Corporation, New York, N. Y., from 1928 to 1935. In 1935 he joined the American Cyanamid Company as electrical designer.

MEMBERSHIP . . .

Recommended for Transfer

The board of examiners, at its meeting of May 16, 1946, recommended the following members for transfer to the grade of membership indicated. Any objections to these transfers should be filed at once with the secretary of the Institute.

To Grade of Fellow

Bettannier, E. L., gen. mgr. & chief engr., Municipal Lt. & Pr. Dept., Pasadena, Calif.
Eastman, A. V., prof. of elec. engg., Univ. of Washington, Seattle, Wash.
Krupp, A. J., sr. engr., Commonwealth Edison Co., Chicago, Ill.
Lomax, C. E., dev. engr., Automatic Elec. Co., Chicago, Ill.
Parker, R. D., telegraph dev. director, Bell Telephone Labs., Inc., New York, N. Y.
Starr, J. H., dev. & mfgr. of elec. equip., 345 N. Spring Ave., LaGrange, Ill.
Winograd, H., engr. in charge, rectifier div., Allis-Chalmers Mfg. Co., Milwaukee, Wis.

7 to grade of Fellow

To Grade of Member

Atwood, A. W., Jr., elec. engr., Southern Calif. Edison Co., Los Angeles, Calif.
Berry, M. D., chief engr., Leland Electric Can., Ltd., Guelph, Ont., Can.
Cowgill, H. A., vice-pres. & div. mgr., Ohio Public Service Co., Port Clinton, Ohio
Dunlop, C. E., elec. supt., Perron Gold Mines, Ltd., Perron, Que., Can.
Ehret, E. L., dist. engr., Westinghouse Lamp Div., St. Louis, Mo.
Erwin, R. A., elec. engg. assoc., Dept. of Water & Pr., Los Angeles, Calif.
Ewald, E., traveling dist. engr., Northern States Pr. Co., Minneapolis, Minn.
Feist, D. N., asst. chief engr., Warner Elevator Mfg. Co., Cincinnati, Ohio
Gronicki, J. J., design engr., General Elec. Co., Lynn, Mass.
Hale, R. M., test engr., Gas Turbine Lab., U. S. Naval Engg. Experiment Station, Annapolis, Md.
Halloran, J. J., production engr., Electro Engg. Works, Oakland, Calif.
Hunt, R. M., requisition engr., General Elec. Co., Pittsfield, Mass.
Kaufmann, H. A., elec. insp. & layout, National Cash Register Co., Dayton, Ohio
Koch, C. R., cons. elec. engr., 2690 Marty Way, Sacramento, Calif.
Lott, H. A., operating engr., Southern Calif. Edison Co., Ltd., Los Angeles, Calif.
Macintyre, J. R., dev. engr., General Elec. Co., Lynn, Mass.
Macpherson, J. F., proposition engr., General Elec. Co., Lynn, Mass.
Maloney, F. V., production engr., Texas Co., Los Angeles, Calif.
Matthews, N. W., engr., head, control systems subsection, U. S. Naval Lab., Washington, D. C.
Mead, M. S., Jr., asst. div. engr., general engg. & cons. lab., General Elec. Co., Schenectady, N. Y.
Miller, C. R., supt., water & elec. dept., Village of Winnetka, Winnetka, Ill.
Milner, M. L., Jr., asst. elec. engr., Illinois Pr. Co., Decatur, Ill.
Mitchell, J. E. M., elec. engr., Porcelain Products, Inc., Parkersburg, W. Va.
Moody, W. S., elec. engr., General Elec. Co., Los Angeles, Calif.
Phillips, G. H., engr., elec. conductor div., Aluminum Co. of America, Pittsburgh, Pa.
Rives, G. S., mgr., H. A. Kuljian & Co., Engrs., Los Angeles, Calif.
Sandlin, D. S., elec. engr., Dow Chemical Co., Freeport, Tex.
Sickel, E. C., substation elec. engr., Northern States Pr. Co., St. Paul, Minn.
Speer, P. B., elec. engr., engg. dept., Northern States Pr. Co., Minneapolis, Minn.
Stehlik, R. F., chief engr., Automatique Electrique, S. A., Antwerp, Belgium
Tandberg, L. G., branch mgr., Wagner Elec. Corp., Los Angeles, Calif.
Wages, R. W., div. ind. pr. engr., Georgia Pr. Co., Columbus, Ga.
Weinstein, H. L., elec. designer, A. Yarus & Sons, Inc., Philadelphia, Pa.
Whitenton, J. M., asst. design engr., elec. instrument div., General Elec. Co., Lynn, Mass.
Winchester, L. J., engr., Bucyrus-Erie Co., So. Milwaukee, Wis.
Worthen, P. A., General Elec. Co., cent. sta. engg., Salt Lake City, Utah

36 to grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Any member objecting to the election of any of these candidates should so inform the secretary before July 15, 1946, or September 15, 1946, if the applicant resides outside of the United States or Canada.

To Grade of Fellow

Grosch, H., Norges Elektriske Materiellkontroll, Oslo, Norway

1 to grade of Fellow

To Grade of Member

Alvarez S., S., Empresa Nacional Calvo Sotelo, Madrid, Spain
Ames, F. H., Jr., General Elec. Co., Schenectady, N. Y.
Ayre, J., Naval Ordnance Depot, York, Pa.
Bennett, G. L., General Elec. Co., Schenectady, N. Y.
Braisted, L., Braisted and Bair, Detroit, Mich.
Bullwinkle, R., Texas Utilities Company, Dallas, Tex.
Burdette, L. W., J. E. Sirrine & Co., Greenville, S. C.
Carter, G. W., University of Oxford, Oxford, England
Davis, H. U., American Tel. and Tel. Co., Philadelphia, Pa.
Dillon, J. F., Public Service Co. of Ind., Inc., Indianapolis, Ind.
Dresser, D. S., Chicopee Mfg. Corp. of N. H., Manchester, N. H.
Duvander, B. H., Clyde E. Bentley, Oakland, Calif.
Eichmann, A. W., Glenn L. Martin Co., Baltimore, Md.
Esson, W. H., General Elec. Co., Pittsfield, Mass.
Gay, H. M., Oklahoma Gas and Elec. Co., Oklahoma City, Okla.
Goodison, A. M., Jr., Westinghouse Elec. Corp., E. Pittsburgh, Pa.
Halsey, T. R., Halsey & Royer, San Antonio, Tex.
Hamm, H. F., New York Naval Shipyard, Brooklyn, N. Y.
Hayward, D. W., Orlando Power Station, Johannesburg, South Africa
Hedgecock, W. A., Consumers Power Co., Flint, Mich.
Hill, D. A., The Austin Co., New York, N. Y.
Hollaway, R. B., The B. F. Goodrich Co., Borger, Tex.
Hotchkiss, C., Perfex Corp., Milwaukee, Wis.
Howard, J. T., The Associated Broadcasters, Inc., and Universal Research Labs., San Francisco, Calif.
Hutton, J. G., General Elec. Co., Schenectady, N. Y.
Kelley, H. W., Rural Electrification Administration, Washington, D. C.
Lightfoot, F. R., Naval Ordnance Lab., Washington, D. C.
Longmire, H. E., General Elec. Co., Detroit, Mich.
Lundberg, O. C., Capitol Elec. Co., San Diego, Calif.
Luttropp, E. S., 18 Lincoln Blvd., Hempstead, N. Y.
Mac Donald, M., Crane Co., Chicago, Ill.
Mackenzie, A. E., E. A. Schmidt & Co., St. Louis, Mo.
McBain, J. W., British Thomson-Houston Co. Ltd., Rugby, England
Mc Bryar, W. R., Westinghouse Elec. Corp., Louisville, Ky.
Mc Keel, W. G., National Carbon Co., Inc., Cleveland, Ohio
Patton, J. H., Sangamo Elec. Co., Springfield, Ill.
Platt, E. R., Foster Transformers and Switchgear, Ltd., South Wimbledon, London, England
Prag, E. R., Carson Machine and Supply Company, Oklahoma City, Okla.
Reisinger, E. J., 9 Laurel Place, W. Caldwell, N. J.
Ryan, R. E., Office of Supervisor of Shipbuilding, Camden, N. J.
Rystedt, S. E., New Jersey Power and Light Co., Dover, N. J.
Scheid, C. A., General Elec. Co., Philadelphia, Pa.
Smith, R. J., Transcontinental and Western Air, Inc., Kansas City, Mo.
Sparke, H., Kirklee's Ltd., Tottington, Bury, Lanc's, England
Staples, J. M., Westinghouse Elec. Corp., Atlanta, Ga.
Stone, R. G., Sr., Tennessee Eastman Corp., Knoxville, Tenn.
Swannell, H. C., J. E. Sirrine & Co., Greenville, S. C.
Schwedes, W. F., Oliver Iron Mining Co., Duluth, Minn.
Tung, Y.-S., Calif. Inst. of Tech., Pasadena, Calif.
Voss, R. S., Bendix Aviation Corp., Philadelphia, Pa.
Ward, J. E., Consumers Power Co., Flint, Mich.
Watson, J. G., British Admiralty Delegation, Washington, D. C.
Weathers, L. C., Vickers, Inc., Detroit, Mich.
Werthmann, F. J., Werthmann Radio Company, Seattle, Wash.
Williamson, J. A., Hydro-Elec. Comm. of Niagara Falls, Niagara Falls, Ont., Can.
Withey, R. B., Consumers Power Co., Flint, Mich.
Wilson, J. M., Minneapolis Honeywell Reg. Co., Minneapolis, Minn.
Wood, E. K., Westinghouse Elec. Corp., E. Pittsburgh, Pa.
Zeh, G. J., U. S. Navy Department, Portland, Oreg.
Zobel, J. A., The Commonwealth and Southern Corp., Birmingham, Ala.

60 to grade of Member

To Grade of Associate

United States and Canada

1. NORTH EASTERN

Akeley, L. T., General Elec. Co., West Lynn, Mass.
Alspach, P. H., General Elec. Co., Schenectady, N. Y.
Andrews, G. M., General Elec. Co., Schenectady, N. Y.
Barnhart, S. S., Jr., General Elec. Co., Schenectady, N. Y.
Bartlett, G., General Elec. Co., Schenectady, N. Y.
Battista, L. M. (Re-election), Children's Village, Hartford, Conn.
Bishop, H. M., Raytheon Mfg. Co., Waltham, Mass.
Briggs, R. H., Eastman Kodak Co., Rochester, N. Y.
Chang, N., General Elec. Co., Schenectady, N. Y.
Clark, R. F., Westinghouse Elec. Corp., Boston, Mass.
Crenshaw, R. M., General Elec. Co., Schenectady, N. Y.
Dimond, H. M., General Elec. Co., Schenectady, N. Y.
Egnor, W. D., General Elec. Co., Schenectady, N. Y.
Fomenko, J. G., General Elec. Co., Schenectady, N. Y.
Harrington, D. R., General Elec. Co., Schenectady, N. Y.
Hart, W. E., Westinghouse Elec. Corp., Boston, Mass.
Henderson, S. D., Westinghouse Elec. Corp., Boston, Mass.
Horton, F. M., Buffalo Niagara Elec. Corp., Buffalo, N. Y.
Johnston, D., Jr., Sunshine Laundry Co., Hartford, Conn.
Leonard, E. H., Jr., Simplex Wire and Cable Co., Cambridge, Mass.
Lundberg, J. E., General Elec. Co., W. Lynn, Mass.
Lurasachi, D. C., Buffalo Niagara Electric Corp., Buffalo, N. Y.
Marts, S. G., General Elec. Co., Schenectady, N. Y.
Metz, E., Bryant Elec. Co., Bridgeport, Conn.
Miller, E. H. (Re-election), W. P. Creager, Consulting Engr., Buffalo, N. Y.
Mitropoulos, T. N., Simplex Wire and Cable Co., Cambridge, Mass.
Morgan, J. M., Jr., General Elec. Co., Schenectady, N. Y.
Olson, S. E., Mass. Inst. of Tech., Cambridge, Mass.
Phillips, C. H., Eastman Kodak Co., Rochester, N. Y.
Pierce, J. L., Harvard University, Cambridge, Mass.
Pitts, L. E., Buffalo Niagara Elec. Corp., Buffalo, N. Y.
Prentice, W. H., General Elec. Co., Boston, Mass.
Rogers, P. R., General Elec. Co., Schenectady, N. Y.
Russell, W. E., Naval Shipyard, Boston, Mass.
Sheets, J., General Elec. Co., Schenectady, N. Y.
Spencer, L. B., Cornell University, Ithaca, N. Y.
Stomski, W. J., General Elec. Co., Schenectady, N. Y.
Stone, D. W., (Re-election), Boston Naval Shipyard, Boston, Mass.
Tulloh, C. A., Jr., General Elec. Co., Schenectady, N. Y.
Wade, R. W., Central Hudson Gas & Elec. Corp., Newburgh, N. Y.
Whitehead, H. S., General Elec. Co., West Lynn, Mass.
Wilson, R. M., Jr., General Elec. Co., Schenectady, N. Y.

2. MIDDLE EASTERN

Ackroyd, P. H., 34 Lewis St., Phillipsburg, N. J.
Ashdown, K. T., General Elec. Co., Philadelphia, Pa.

Bishop, C. K., Crise Manufacturing Co., Columbus, Ohio
Bramble, J. H., Westinghouse Elec. Corp., Sharon, Pa.
Buckhold, J. F., Clark Controller Co., Cleveland, Ohio
Bundry, O. M., The Clark Controller Company, Cleveland, Ohio
Carleton, J. T., Westinghouse Elec. Corp., E. Pittsburgh, Pa.
Clark, W. H., Naval Research Laboratory, Washington, D. C.
Davis, R. T., Plate Ice Co. & Corbett Package Co., Wilmington, N. C.
Dickason, R. J., The General Elec. Co., Erie, Pa.
Frost, H. J., Ohio Bell Tel. Co., Cleveland, Ohio
Guarino, L. S., Naval Air Experiment Station, Philadelphia, Pa.
Henson, R. J., General Elec. Co., Philadelphia, Pa.
Hernick, P. W., Westinghouse Elec. Corp., E. Pittsburgh, Pa.
Hunt, W. A., Philadelphia Elec. Co., Philadelphia, Pa.
Hurd, T. J., Rural Electrification Administration, Washington, D. C.
Jarrett, E. L., Duquesne Light Co., Pittsburgh, Pa.
Johnson, E. C., Chesapeake and Potomac Tel. Co., Charleston, W. Va.
Johnson, W. H., Phila. Elec. Co., Philadelphia, Pa.
Kelly, R. E., Westinghouse Elec. Corp., East Pittsburgh, Pa.
Kline, R. H., Westinghouse Elec. Corp., E. Pittsburgh, Pa.
Lee, C. F., 701 Shafor Blvd., Dayton 9, Ohio
Lindley, L. E., Jr., Sylvania Elec. Products, Inc., Emporium, Pa.
Middleton, W. W., Capt., 511 East Pitt St., Bedford, Pa.
Moore, H. D., General Elec. Co., Philadelphia, Pa.
Pink, J. F., E. I. Du Pont & Co., Wilmington, Del.
Piotrowski, E. T., Pennsylvania Transformer Co., Pittsburgh, Pa.
Pitcher, W. J., Dayton Power & Light Co., Dayton, Ohio
Reese, H. N., Baltimore Transit Co., Baltimore, Md.
Roberts, C. A., Jr., United Engrs. & Const., Inc., Philadelphia, Pa.
Robertson, H. E., Westinghouse Elec. Corp., Baltimore, Md.
Roylance, T. A., RCA Victor, Camden, N. J.
Schafrik, E. M., Clark Controller Co., Cleveland, Ohio
Schultz, V. W., Firestone Tire & Rubber Co., Akron, Ohio
Smitheman, E. W., Philadelphia Naval Shipbuilding Yard, Philadelphia, Pa.
Snider, R. T., Virginian Elec. Inc., Charleston, W. Va.
Tittermary, J. R., Philadelphia Elec. Co., Philadelphia, Pa.
Weller, R., Locke Insulator Corp., Baltimore, Md.
Wendling, L. W., Navy Dept., Bureau of Ships, Washington, D. C.
Wilson, H. T. (Re-election), Appalachian Elec. Power Co., Bluefield, W. Va.
Wittenberg, H. H., RCA Victor Division, Lancaster, Pa.

3. New York City

Bonahur, A. A., S. J. O'Brien, Inc., New York, N. Y.
Broschc, M. F., New York Tel. Co., New York, N. Y.
Brownman, H. L., Polytechnic Institute of Brooklyn, Brooklyn, N. Y.
Derman, J., Watson Labs., Air Technical Service Command, Red Bank, N. J.
Genon, L. B., General Elec. Co., New York, N. Y.
Howard, J. J., Watson-Flagg Eng. Co., Inc., New York, N. Y.
Kline, A., Garod Radio Corp., Brooklyn, N. Y.
Melillo, V., Voorhees Walker Foley & Smith, New York, N. Y.
Miller, T. W., The Teleregister Corp., New York, N. Y.
Oxhandler, R., Board of Transportation, New York, N. Y.
Renton, V. S., Public Service Elec. & Gas Co., Newark, N. J.
Small, C. S., Baker and Spencer, Inc., New York, N. Y.
Tapley, J. G., Crocker-Wheeler Elec. Co., Ampere, N. J.
Thoma, H. G., The Linde Air Products Co., New York, N. Y.
Tobin, M., Syska & Hennessey, New York, N. Y.
Vitrogan, D., Brooklyn Polytechnic Institute, Brooklyn, N. Y.

4. Southern

Ellis, W. R., Duke Power Co., Greenville, S. C.
Farrell, J. M., Carolina Elec. Supply Co., Charlotte, N. C.
Halpern, W., U. S. Navy, Portsmouth, Va.
Henning, A. F., Jr., Geo. M. Meriwether, Industrial Equipment, Birmingham, Ala.
Kalus, N. S., Tennessee Valley Authority, Memphis, Tenn.
Keithler, G. K., Jr., Lt., The Engineer School, Ft. Belvoir, Va.
Johnson, F. L., Southwestern Gas and Elec. Co., Shreveport, La.
Mc Iver, A. B., Southwestern Gas and Elec. Co., Shreveport, La.
Noland, J. H., Jr., University of S. C., Columbia, S. C.
Sander, W. A., Jr., U. S. Naval Shipyard, Charleston, S. C.
Walker, H. K., Tennessee Valley Authority, Wilson Dam, Ala.
Webb, J. F., Jr., Alabama Power Co., Birmingham, Ala.

5. Great Lakes

Bachman, R. H., Caterpillar Tractor Co., East Peoria, Ill.
Binak, F., 13751 Conley Ave., Detroit, Mich.
Black, K. G., Square D Co., Milwaukee, Wis.
Blackman, C. H., Burroughs Adding Machine Co., Detroit, Mich.
Bloch, W. C., General Elec. Co., Fort Wayne, Ind.
Bremner, W. C., Commonwealth Edison Co., Chicago, Ill.
Burnham, G. C., Allen-Bradley Co., Milwaukee, Wis.
Crampton, H. E., Michigan Bell Tel. Co., Detroit, Mich.
Dickman, E. W., (re-election). Northwestern Aero Corp., St. Paul, Minn.
Fenton, E. L., Veterans Administration, Minneapolis, Minn.
Fischer, P. M., Cutler-Hammer Corp., Milwaukee, Wis.
Gellatly, J. S., Western Elec. Co., Inc., Chicago, Ill.
Grant, J. W., Armour Research Foundation, Chicago, Ill.
Karl, D. R., 2616 South Adams St., Peoria, Ill.
Klein, B., Sargent & Lundy, Chicago, Ill.
Knapp, T. F., Lear, Inc., Grand Rapids, Mich.
Kocherar, J. S., Minnesota Power & Light Co., Duluth, Minn.
Kuester, A. J., Vern E. Alden Co., Chicago, Ill.
La Rose, A. F., Electra-Voice Corp., Chicago, Ill.
Lofquist, C. A., Caterpillar Tractor Co., E. Peoria, Ill.
Maclague, H. K., Guardian Elec. Manufacturing Co., Chicago, Ill.
McCauley, W. B., General Elec. Co., Fort Wayne, Ind.
Meyer, I., Appleton Elec. Co., Chicago, Ill.
Nemetz, V. W., Public Service Comm. of Wis., Madison, Wis.
Newman, E. N., Reynolds Metals Co., McCook, Ill.
O'Hare, E. F., Western Elec. Co., Chicago, Ill.
Parrott, J. R., Commonwealth Edison Co., Chicago, Ill.
Rehm, F. J., Commonwealth Edison Co., Chicago, Ill.
Roasa, H. L., Commonwealth Edison Co., Chicago, Ill.
Roesukranz, H. G., Allen-Bradley Co., Milwaukee, Wis.
Saylen, H. W., 1219 Knoxville Ave., Peoria, Ill.
Schaudenecker, A. F., Western Elec. Co., Chicago, Ill.
Schneider, R. C., Illinois Power Co., Belleville, Ill.
Sherman, R. E., 411 Ludington Ave., Menominee, Mich.
Stearns, F. V., Western Elec. Co., Cicero, Ill.
Stratton, M. L., A.C. Spark Plug Division of General Motors, Flint, Mich.
Teasdale, R. D., Ill. Inst. of Tech., Chicago, Ill.
Thornberry, H. C., Allen-Bradley Co., Milwaukee, Wis.
Van Camp, F. E., Commonwealth and Southern Corp., Jackson, Mich.
Vinci, C. F., Rockford Machine Tool Co., Rockford, Ill.
Weinberger, S. M., Allis-Chalmers Mfg. Co., Milwaukee, Wis.

6. North Central

Erickson, H. N., Nebraska Public Power System, Omaha, Nebr.
Weber, J. D., Mountain States Tel. & Tel. Co., Denver, Colo.

7. South West

Baird, J. W., Gulf States Utilities Co., Beaumont, Tex.
Beck, C. W., Aluminum Company of America, Dallas, Tex.
Boise, D. R., Allis-Chalmers Mfg. Co., San Antonio, Tex.
Bridler, F. W., El Paso Elec. Co., El Paso, Tex.
Bukovatz, J. E., Fairbanks-Morse & Co., Kansas City, Mo.
Coxe, W. D., Dow Chemical Co., Freeport, Tex.
Henderson, G. W., Dallas Power & Light Co., Dallas, Tex.
Hutto, R. L., U. S. Engineer Office, Little Rock, Ark.
Leach, C. C., Syndicate Trust & Century Bldgs., St. Louis, Mo.
Robertson, O. L., The Elec. Storage Battery Co., Dallas, Tex.
Smith, F. K., Westinghouse Elec. Corp., Houston, Tex.
Zimmer, H. I., Jr., El Paso Elec. Co., El Paso, Tex.

8. Pacific

Allen, M., United Aircraft Products, Inc., Los Angeles, Calif.
Anderson, S. C., Pacific Gas & Elec. Co., San Francisco, Calif.
Arnerich, P. F., Douglas Aircraft Co., Santa Monica, Calif.
Baker, L. S., Consolidated Vultee Aircraft Corp., San Diego, Calif.
Bullock, H. H., General Elec. Co., Phoenix, Ariz.
Clack, J. F., Arizona Edison Co., Bisbee, Ariz.
Dusterberry, J. C., Nat'l Advisory Comm. for Aeronautics, Moffett Field, Calif.
Erickson, T. W., Pacific Gas and Elec. Co., Oakland, Calif.
Estes, B. E., U. S. Naval Air Station, Alameda, Calif.
Gilcrest, G. B., General Elec. Co., San Francisco, Calif.
Glaser, W. D., General Elec. Co., San Francisco, Calif.
Hawley, P. F., Consolidated Engg. Corp., Pasadena, Calif.
Huska, P., Douglas Aircraft Co., El Segundo, Calif.
Marshall, W. C., USNR, F.P.O., San Francisco, Calif.
Mayfield, F. E., Standard Oil of Calif., Richmond, Calif.
McDermitt, G. S., Arizona Light & Power Co., Phoenix, Ariz.
Neiswander, R. S., Calif. Inst. of Tech., Pasadena, Calif.
Peterman, H. A., Hyperion Project, Los Angeles, Calif.
Phelps, A. H., Westinghouse Elec. Corp., Sacramento, Calif.
Pridemore, F. W., George Young Co., Los Angeles, Calif.
Sibley, S. L., Pacific Gas and Elec. Co., San Francisco, Calif.
Taylor, G. W., 1955-A Jackson St., San Francisco, Calif.
Wortman, J. W., Ens., USNR, Ames Aeronautical Lab., Moffett Field, Calif.

9. North West

Alexander, A. I., Westinghouse Elec. Corp., Portland, Oreg.
Anderson, R. W., Lt. (jg) USNR, Tacoma Group, Nineteenth Fleet, Tacoma, Wash.
Bredemeier, G. E., Portland General Elec. Co., Portland, Oreg.
Burns, T. W., Commercial Iron Works, Portland, Oreg.
Dillow, J. C., Westinghouse Elec. Co., Portland, Oreg.
Estberg, N. L., Bonneville Power Administration, Portland, Oreg.
Fromm, F. W., 13th Naval District, Headquarters, Seattle, Wash.
Jarrett, C. W., Portland General Elec. Co., Portland, Oreg.
Jower, J. W., Commercial Iron Works, Portland, Oreg.
Kall, W. L., Bonneville Power Administration, Portland, Oreg.
Lawrence, S. E., Abernathy Road, Oregon City, Oreg.
Lester, H. D., U. S. Navy (Civil), Portland, Oreg.
Lundquist, A. H., Bonneville Power Administration, Vancouver, Wash.
Lundquist, L. E., U. S. Navy, Portland, Oreg.
Miller, D. R., Portland General Elec. Co., Portland, Oreg.
Moreland, W. J., Westinghouse Supply, Portland, Oreg.
Nicholson, W. I., General Elec. Co., Portland, Oreg.
Osipovich, A. A., Bonneville Power Administration, Portland, Oreg.
Porter, J. D., Bonneville Power Administration, Vancouver, Wash.
Seymour, R. S., Bonneville Power Administration, Portland, Oreg.
Strand, L. E., Commercial Iron Works, Portland, Oreg.
Swarner, J. H. (Re-election), Bonneville Power Administration, Portland, Oreg.
Tatit, R., Bonneville Power Administration, Portland, Oreg.
Udy, G. W., The Pacific Tel. & Tel. Co., Portland, Oreg.
Wagenknecht, M. A., Portland General Elec. Co., Portland, Oreg.

10. Canada

Coxon, P. A., Hydro Electric Power Comm. of Ont., Toronto, Ontario, Canada
Fraser, W. J. S., Dept. of Trade & Commerce, Dominion Govt., Vancouver, B. C., Can.
Karkheck, H., Mercury Mills, Hamilton, Ontario, Canada
Louie, J., Cemco Electrical Manufacturing Company, Ltd., Vancouver, B. C., Canada
Pilrainen, G. O., Sudbury Hydro Electric Commission, Sudbury, Ontario, Canada

Elsewhere

Dahlberg, R. S., Jr., Creole Petroleum Corporation, Caracas, Venezuela, S. A.
de Amarante, E., Escola Nacional de Engenharia da Universidade do Brasil, Rio de Janeiro, Brasil, S. A.
Eliopoulos, E. T., The Sun Engineering Company, Cairo, Egypt
Garciatorres T., A., Mexican Light and Power Company, Ltd., Mexico D. F., Mexico
Gutierrez Gro., R., Mexican Light and Power Co., Mexico D. F., Mexico
Lowe, I., Wellington Technical College, Wellington, New Zealand
Olverholm, H., A.S.E.A., Vasteras, Sweden
Perez, C. P., International Standard Electric, Buenos Aires, Argentina
Powell, J. E., State Hydro-Elec. Dept., Auckland, New Zealand
Qadri, N. H., The British Institute of Engg. Tech., London, England
Rable, M. M., Ministry of Public Works, Cairo, Egypt
Rolfe, E. Capt., Royal Elect. & Mech. Engrs., War Office, London, England
Rouse, F. W. D., Admiralty Signal Establishment, Glossop, Derbys., England
Tidd, J. L., Heiemano Receiver Site, Oahu, T. of Hawaii

Total to grade of Associate
United States and Canada, 219
Elsewhere, 14

OF CURRENT INTEREST

Improved Facsimile Systems Demonstrated for the Press

Two facsimile systems showing many advances over prewar models recently were demonstrated for the press in New York, N. Y. The Finch Telefax was on view at the American Newspapers Publishers meeting in the Waldorf Astoria, and the Hogan Faximile System was demonstrated in the laboratory of Radio Inventions, Inc. J. V. L. Hogan (M '20) is president of the firm manufacturing the latter equipment, and W. G. H. Finch (M '26) is president of Finch Telecommunications, manufacturer of the Telefax.

Both sets are capable of reproducing and transmitting any black and white copy—photographs, diagrams, printed or handwritten material, or tabular matter—with greater speed, clearer definition, and larger page size than models used either before the war or during the war in Government operations.

However, the Finch company concentrated on facsimile as a new means of communication specially useful to police, railroads, interplant and interoffice transmission, mining and other industries with remote installations, forestry services, aviation, department stores, and shipping. The Hogan demonstration was concerned mainly with its possibilities as a broadcasting medium for use in conjunction with radio.

Speeds of from 15 square inches per minute to 48 square inches per minute have been attained by the Finch machine for which deliveries to the general public are expected for the early fall of 1946. The over-all size of the combined sending and receiving unit is about that of a standard typewriter.

The wide diversity of copy presented at the Hogan demonstration, ranged from news pictures, matter to accompany household programs such as recipes and sample menus, weather maps, comments on musical numbers and pictures and life stories of composers, cartoons, crossword puzzles, instruction texts and reference reading for educational programs, and special bulletin newspapers, made up in half pages tabloid size. The programs included pages designed for association with sound programs as a means of amplifying their entertainment or educational values.

Copy comes out of the home recorder with type matter of newsmagazine size appearing much faster than it can be read. During the usual 15-minute broadcast, four pages of illustrated reference copy can be transmitted by frequency modulation radio and reproduced in the home, thus permitting a 15-minute newscaster on an amplitude modulation station, for example, to accompany his spoken word on an associated frequency modulation station with 4,000 words of printed text or four pages of maps, diagrams, and photographs. The format was selected to permit four column layouts of standard newspaper size.

All of this is accomplished by a simple mechanism for converting the received picture broadcasting signal to a black line proportionate to the intensity of the shading of the picture being transmitted. These lines are drawn transversely on a continuous roll of recording paper and blend into an accurate reproduction of any kind of written, printed, drawn or photographic information.

The recording paper turns black to a degree controlled by the moment-to-moment intensity of the picture signal being received. The Hogan system uses an electrochemical process for attaining the black which eliminates all photographic finishing, the use of ink, or paper surface burning often associated with facsimile operation.

At the broadcasting station the copy to be transmitted is progressively scanned by an electric eye through a lens system at the rate of 105 lines per inch with a horizontal definition equivalent to over 100 lines per inch. The copy at the transmitter is mounted on a cylindrical drum for submission to the optical system which scans or analyzes 28.1 square inches of copy per minute. The electric eye varies the intensity of the current as the changes in the light intensity submitted from the subject matter. The frequency of the picture signal thus produced varies from 7,000 to 13,000 cycles, suiting it to radiation by any frequency modulation broadcasting station. This is the maximum speed obtainable by reason of band-width limitations of frequency modulation broadcast frequency allocations, but it will be entirely adequate for home purposes, since 16 pages of copy can be reproduced each hour.

The home recorder is loaded with 400 linear feet of the specially treated paper, enough for 24 continuous hours of reception or two to four weeks of home service. Reloading the paper supply is comparable with loading a simple camera.

The received picture signal is delivered to the home recorder from any frequency modulation receiver capable of receiving regular frequency modulation sound broadcast. The recorder includes a small amplifier for bringing the signal up to the necessary levels to pass it through the recording paper.

The Faximile recorder which prints in the radio set owner's home is a little larger than a portable typewriter. It may be manufactured for mounting in its own cabinet to be attached to a radio set already in the home, or it may be built into a radio console by the manufacturer.

There are no rapid reciprocating mechanical motions in the mechanism; the electrical contact for passing the received picture signal through the paper is made from a printer blade over the paper to a wire helix mounted on a drum which rotates at the slow rate of 360 rpm, which it is claimed will prolong the life of the apparatus. All the user need do is to tune in the station desired, turn on the recorder, and adjust the volume control.

One model of the home type recorder shown at the demonstration was equipped with an automatic synchronizer which makes it unnecessary for transmitting scanner and recorder to rely on the same power system, a problem encountered in some cities having partly d-c power supply or competing a-c power systems. It is expected that this device will not be incorporated in all recorders manufactured, as it is unnecessary in 80 per cent of the United States.

It is possible to install scanners in mobile units together with photographic equipment for finishing and broadcasting photographs taken at spot news and sporting events. When mass production of recorders for sale to the general public will begin is a matter of conjecture. However, no one familiar with the situation at the demonstration would predict that recorders would appear for general sale in less than a year.

At the present time, it appears that facsimile schedules may begin in about 15 leading cities within the next six months, primarily with a view to developing presentation techniques and determining public reaction to them. Apparatus will be manufactured by the General Electric Company, and the first program explorations to determine public reaction are expected to begin early in the winter of 1946.

British Cable Plans Include One Global Rate

Complete public ownership of Cable and Wireless, Ltd., British communications monopoly, and a standard world ceiling rate for cable or wireless communications were included in plans for the future development of the communication industries recently made public by the British Government.

The Government will purchase all shares, of which it already owns eight per cent,

of the Cable and Wireless company. The company's assets also include substantial holdings in the Dominion and the Indian companies. With Parliamentary approval, a Commonwealth Communications Board will be established to replace the Commonwealth Communication Council set up in 1945, following the London Communications Conference.

A standard world ceiling rate of 30 cents a word for cable and wireless messages has been set as one of the Government's goals, in accordance with the Bermuda agreement of December 1945.

German and British War Lighting Topic for U. S. Committee of ICI

Reports on lighting practice and developments in England and Germany during the war were made to the first postwar annual meeting of the United States National Committee of the International Commission on Illumination, November 1, 1945. Observations made on trips through England and Western Europe in the summer of 1945 were presented by Samuel G. Hibben (M '45) director of applied lighting, lamp division, Westinghouse Electric Corporation, Bloomfield, N. J.; and J. L. Kilpatrick (A '09) New York, N. Y.

Predictions of an expansion of fluorescent lighting in England stimulated by the necessity of fuel conservation and the urge to modernize the lighting of industry were made. High intensity mercury lighting also seems destined for considerable expansion, according to the reports. This was given a prewar tryout in both Germany and England, and a noticeable growth of mercury street and highway lighting has occurred in the British Isles. A wider variety of wattage sizes than are now standard in the United States have been used. High mounting, prismatic glassware control, and some serious problems of glare are involved in the installations.

Among the wartime casualties were tinted incandescent lamps, except those used for blackout purposes, and sodium and mercury installations which were discontinued in Germany and neighboring countries subject to bombing because of their peculiar color.

Applications of interior treatments to benefit lighting, such as hand painting machine tools and the use of colors designed to facilitate safe handling, still appear to be lacking in Western Europe.

Wartime automobile lighting in Germany concentrated upon the use of one driving headlamp mounted in the center or on the mudguard at the left side at the height of the regular headlamp. Statistics in England indicate that street traffic accidents increased because of dimout, in spite of curtailed vehicular traffic. A slight increase in illumination tended to increase the number of pedestrians and therefore the number of accidents.

By August 1945 most of England's street lighting was back to prewar conditions and functioning on regular schedules. In June most of the suburban and residential areas of German cities were supplied electric service for homes and residence lighting was in good shape, with reduced wattages of bulbs but with fittings comparable in quality and illumination supplied to those of the average middle class American home.

Street lighting in Germany conformed to international practice, but close spacing, high mounting, and sharp cutoff provided easier seeing conditions than those usually found in the United States.

Most of the technical high schools (colleges) in Germany conducted courses in illumination and awarded degrees in that study.

Both observers emphasized that in Germany all lighting standards and practice deteriorated progressively with the increase in bombing activity, until by the end of the war, local lighting from adjustable reflectors was most prevalent for industrial operations and bare incandescent lamps and exposed wiring were used for the little general illumination in operation.

In general, there was very little progress in the field of illumination in Germany during the war. Lighting research was primarily for blackout purposes and improvement of searchlights. In Mr. Kilpatrick's opinion the greatest obstacle to gleaning any data of real import lay in the fact that Berlin was the fountainhead of lighting knowledge in Germany and all worth-while equipment and personnel in all branches of industry were removed by the Russians prior to occupancy by British–American forces. Considerable work had been done in the infrared field in connection with radar development. There was a reported development of a 15-kw air-cooled mercury vapor lamp, but this was one of the Berlin items which had been removed.

Other matters discussed at the ICI meeting pertained to action needed to re-establish the smooth working of the international organization disrupted by the war. It was decided to propose to the central bureau of the ICI that of the Secretariats assigned to Germany in 1939 the United States National Committee take over the responsibility for colorimetry, lighting education, and the lighting of motion picture houses. It was thought that Great Britain would wish to take over the subject of natural daylight.

It was reported that organization is under way of the International Standards Co-ordinating Association, first meeting of which was held in London, England, May 27, 1946. As standardization is only a minor activity of the ICI, the United States committee agreed that there is no reason for the ICI to be dissolved and become a section of the new association, as has been suggested. The ICI will participate in the work of the association, however.

Distribution of copies of the unofficial version of the 1939 *Proceedings* of the ICI was considered, and it was voted to mail two copies to each national committee.

It also was decided to recommend that in future ICI *Proceedings* English be adopted as the official language.

It was learned that the Germans had issued two volumes of *Proceedings* of the 1939 sessions, copies of which are in the hands of some delegates to the last ICI meeting. None of these has reached the United States committee.

Preston S. Millar (M '13) president of the committee, presided and Doctor N. A. Halbertsma, of Holland who was elected president of the ICI in 1939, addressed the meeting on conditions in Europe and what the United States committee might do to assist in the revival of international lighting activities.

Others present at the meeting were:

D. W. Atwater (A '34), A. A. Brainerd, F. C. Breckenridge, A. D. Cameron, C. B. Conway (A '44), E. C. Crittenden, Hawthorne Deming, C. D. Fawcett (M '20), W. F. Forsythe, Ward Harrison (F '34), B. J. Hessen, W. C. Kalb (F '40), G. H. Stickney (F '24), F. V. Westermaier.

Silver Supply for Industry Nears Vanishing Point

The estimated production of silver for 1946 will be 44 per cent below the prewar level, which represents less than one quarter of that needed by American industries, according to a recent statement by the Silver Users Emergency Committee advocating Senate action on bills authorizing treasury sale of some surplus metal to industry.

The supply of the metal available to the silver using industries generally this year has varied from around 30 per cent of the volume needed in January to less than five per cent of requirements for some industries in April, the committee states. This worsening situation is attributed to the efforts of Senators from the silver-producing states to block consideration of the bills passed by the House of Representatives which would release some of the Treasury's stock of free silver for purchase by industry.

The silver bloc in the Senate meanwhile has been crusading to force the price of silver, whether for industrial or monetary use, to $1.29 an ounce. The present ceiling price is 71 cents, and the prewar level was about 35 cents.

Electric equipment industries will need 10 million ounces of silver in 1946. The cost of the year's supply at the present ceiling would be $7,100,000, and the proposed increase in price would add $5,800,000 to this bill.

No relief can be expected from foreign sources while Senate action is pending, as foreign owners are hoarding available supplies in the hope of a price advance.

CIGRE Resumes Sessions in Paris June 27 to July 6

The first plenary session since 1939 of the International Conference on Large Electric High-Voltage Systems (Conference Internationale des Grands Réseaux Electriques à Haute Tension) will be held in Paris, France, as is customary, from June 27 to July 6. Of the 100 technical papers to be presented, 10 are expected from United States authors. This is a better representation than at the 1939 session when only 5 of the 117 papers were of United States authorship.

Established in 1921 as a permanent international association, the Conference provides an international exchange of engineering information relating to the design, construction, and operation of large high-voltage electric systems. Biennial sessions are held in Paris, headquarters of the organization, at which delegates from all participating countries present and discuss technical papers and at which the international technical committees appointed by the CIGRE submit reports on results of interim studies. Anyone who complies with the conditions of membership may participate in these meetings subject to the permission of the national committee for his country.

Though not all the problems discussed are new in the United States, the extension of higher voltages and large interconnected systems in all parts of the world has developed operating experiences which are of value to American engineers engaged in the design and operation of similar systems. United States engineers engaged in the design of apparatus, equipment, and devices entering into these systems also are afforded a broad view of trends in engineering design throughout the world and the opportunity to disclose the merits of their own design and practice.

Also, since the proceedings, discussions and findings of CIGRE are submitted to the International Electrotechnical Commission for its consideration in the establishment of international electrical standards, the CIGRE sessions offer a valuable opportunity to American engineers and agencies interested in standards to take part in the preliminary and formative discussions incident to the CIGRE sessions.

The continuity of the work of the Conference between sessions is ensured by international technical committees. The 14 at present in existence are:

A-c transmission at extra high voltage, chairman, Philip Sporn (F '30); d-c transmission, chairman, Mr. Borgquist of Sweden; insulation materials; underground cables, chairman, Mr. Bakker of Holland; insulation oils, chairman, Mr. Weiss of France; circuit breakers, chairman, Mr. Juillard of Switzerland; improvement of power factor; surges, chairman, Mr. de Bisuera of Spain; insulators, chairman, Mr. Van Cauwenberghe of Belgium; co-operation with international telephone consulting committee, chairman, Mr. Charpentier of France; overhead conductors, chairman, Mr. Jacobsen of Norway; towers and foundations, chairman, Mr. Lavanchy of Belgium; mechanical calculations of lines, chairman, Mr. List of Czechoslovakia; and telephone and radio interference.

CIGRE also maintains national committees of the countries participating in its activities. These enroll memberships, assign and review technical papers for the sessions, and appoint members of the technical committees. The United States National Committee follows:

Frederic Attwood (M '27), J. C. Parker (F '12), I. W. Gross (F '45), Philip Sporn, W. W. Lewis (F '38), J. B. Whitehead (F '12), W. S. Peterson (M '29), P. L. Bellaschi (F '40), E. L. Moreland (F '21), M. S. Oldacre (M '42), Stanley Stokes (F '29), L. N. McClellan (F '38), S. H. Mortensen (F '20), Walker L. Cisler (M '35), William E. Wickenden (F '39) *ex-officio*, H. J. Scholz (M '39), H. L. Melvin (F '31), T. J. Little (M '45), Gano Dunn (HM '45).

Memberships in the United States may be individual or collective. In the first category regular members pay annual dues of $10 and associate members pay $5. Collective memberships may be sustaining, regular, or associate. For industrial, manufacturing, and consulting engineering companies, financial companies, public agencies of commercial character, universities and other institutes of learning or research, and all other noncommercial collective bodies the annual dues are $500, $100, and $50, respectively for the three grades of membership. Government and other public administrations and agencies and technical associations pay $1,000, $200, or $100 annually.

All individual members receive advance copies in English of all technical papers presented at the biennial sessions. All collective members receive copies of the bound proceedings in English.

Formal recognition of the CIGRE association and its biennial sessions is given by the State Department through the appointment of an official delegation to represent the United States Government, selected from the United States delegates attending the biennial sessions.

Registration by Endorsement Provided by National Bureau

The procedure and purpose of the registration service rendered engineers by the National Bureau of Engineering Registration is described in a recent information pamphlet issued by the Bureau. The Bureau was established primarily to minimize the effort and expense of engineers desiring to secure registration or license in more than one state.

Operated by the National Council of State Boards of Engineering Examiners, the Bureau is under the direction of a standing committee of the Council with an advisory board of representatives from national engineering societies. A secondary purpose of the Bureau is to act as a clearing house for state registration authorities, employers, societies, and others, acting as a reliable source of verified information regarding the professional records of engineers.

Endorsement by the National Council as well as by a state board usually means that an application for registration in various states will be expedited and promptly approved. To obtain such endorsement an

Classroom Mural to Inspire Freshmen

This representative engineering student surrounded by typical end products of his training is depicted in a four by eight foot photographic mural recently hung on the wall of the engineering drawing classroom at Cooper Union, New York, N. Y.

engineer files an application for a certificate of qualification with the National Bureau of Engineering Registration which will secure the endorsement of the state board of registration of his home state and, after verifying the professional record of the applicant will affix its endorsement, and the seal of the National Council.

The bylaws of the National Council and the registration laws or regulations of most states specifically provide for recognition of certificates of qualification issued by the Bureau, and all member boards of the Council accept certification by the Bureau, with endorsement by a state board as competent evidence of qualification for registration. However, all state boards reserve the right to take whatever action they deem necessary to conform with the requirements of their laws and regulations in connection with any application for registration in their state.

Any registered engineer desiring a certificate of qualification must submit to the Bureau on its prescribed form his complete record, including education, engineering experience, legal registration, technical examinations, membership in professional or scientific societies, and character and professional references.

This application then is submitted by the Bureau to the registration board in the state of which the applicant is a resident or in which he is practicing. The Board may require the applicant to furnish additional information or to pass an examination to establish his competency. Once this is established, the Board endorses the certificate of qualification to the effect that the applicant is entitled to be recommended to other state boards for registration. At this point the Bureau makes an independent investigation of each item in the applicant's record, verifying them or giving reasons for not doing so.

After this, the Bureau evaluates the professional record of the applicant and issues a certificate of qualification, if he meets the requirements of one of the following sections.

Graduation Plus Experience. Graduation from an engineering curriculum accredited by the Engineers' Council for Professional Development, and a specific record of eight years or more of experience in engineering work of a character satisfactory to the Bureau. Where the evidence presented does not appear to the Bureau conclusive, the applicant may be required to present further evidence for the Bureau and to pass examination (given by the registration board in his home state).

Examination Plus Experience. Successfully passing an examination (given by the registration board in his home state) designed to show knowledge and skill approximating that attained through graduation from an accredited engineering curriculum; and a specific record of eight years or more of experience in engineering work of a character satisfactory to the Bureau.

Long Established Practice. A specific record of 15 years or more of lawful practice in engineering work of a character satisfactory to the Bureau, provided the applicant is not less than 35 years of age.

Demonstration of applicants' competency will be based less on length of experience (provided the minimum is met in each case) than on the breadth, quality, and importance of pertinent experience, degree of progression, evidence shown of ability to accept increasing responsibilities, and of the possession of personal qualifications required for successful engineering work.

The fee for investigation, verification, and certification, including one photostatic copy of completed verified professional record, certificate of qualification, and state board endorsement is $20. Additional copies are $2 each. These fees represent actual cost of the work involved, as the Bureau is a nonprofit agency.

Engineers desiring legal registration or license in any state must communicate directly with the state board in question and secure its application form and regulations. Applications for registration by endorsement must be accompanied by photostatic copies, issued by the Registration Bureau, of certificates of qualification.

Members of the committee on National Bureau of Engineering Registration are:

L. M. Martin, chairman, representing the committee on qualifications for registration; C. C. Knipmeyer, (M '35), Indiana, representing the committee on Engineers Council for Professional Development; Roy M. Green, Nebraska, representing central zone; Joseph Weil (F '36), Florida, representing southern zone; A. G. Christie, Maryland, representing northeast zone; Daniel B. Jett, New Mexico, representing western zone; T. Keith Legaré, South Carolina, executive secretary, National Council of State Boards of Engineering Examiners.

Members of the advisory board are: American Society of Civil Engineers, Allen P. Richmond, Jr.; American Society of Mechanical Engineers, William G. Christy; AIEE, C. R. Beardsley (F '30); American Institute of Chemical Engineers, J. M. Weiss; National Society of Professional Engineers, Arthur V. Sheridan; Society for the Promotion of Engineering Education, Paul Cloke (F '38); American Association of Engineers, C. J. Ullrich; American Railway Engineering Association, R. E. Warden.

Army Used Infrared Radiation to Detect in Total Darkness

The use of infrared radiation for observation in total darkness by the United States Armed Forces, another of World War II's secret weapons, was revealed recently by the United States Army upon information that the Germans had utilized similar, though inferior and less effective, equipment.

The device is available in two models, a "sniperscope" mounted on a 30 caliber carbine and a "snooperscope," a hand model used for observation and signaling. The equipment employs a light source which, through filters, cuts out the "visible light" of the spectrum and transmits infrared radiation. The reflected infrared radiation is picked up by the objective lens of a telescope and focused on a photoelectric image tube. When the infrared rays strike this tube, electrons are released in direct proportion to the intensity of the radiation and, as all electrons possess a negative charge, the released electrons are attracted by the positive plates. These electrons are accelerated as they pass through the tube to bombard a fluorescent screen and thus produce a visible image corresponding to the infrared image on the front screen.

The device is operated by focusing it in the desired direction and moving it back and forth until the object is picked up by the invisible radiation. The visible image can be seen in the telescope by the operator who then may sight his gun.

Power packs for the device were manufactured by Electronics Laboratories, Inc., Indianapolis, Ind.; photoelectric tubes by Farnsworth Television and Radio Corporation, Fort Wayne; and telescope lenses by Bell and Howell Company, Chicago, Ill.

U. S. Engineers Resume Work on Southwest Flood Control

Temporarily suspended by the war emergency, flood control projects in the Southwest are again under construction, the office of the Southwestern Division Engineer, of the United States Corps of Engineers recently announced.

The first project upon which work has been resumed is the Canton Dam project, a $5,192,623 undertaking, on the North Canadian River above Oklahoma City, Okla. Work on Canton Dam was 25 per cent completed when it was placed in a stand-by status at the beginning of the war. When completed, the dam will create a reservoir with a total storage capacity of 390,000 acre-feet of water and will cover an approximate area of 15,500 acres. The dam will be 14,300 feet long, 32 feet wide at the crest, and 68 feet above the valley floor.

In addition to the Canton Dam th: projects include: Wister Dam and reservoir on the Poteau River near the Oklahoma–Arkansas state boundary; the Fort Gibson Dam and reservoir on the Grand (Neosho) River near Muskogee, Okla.; the Hulah Dam and reservoir on the Caney River near the Oklahoma–Kansas state boundary; completion of the existing John Martin Dam and reservoir on the Arkansas River near Las Animas, Colo., by the installation of spillway gates; the Blue Mountain Dam and reservoir on the Petit Jean River west of Little Rock, Ark.; the Bull Shoals Dam and reservoir on the White River near the Arkansas–Missouri state boundary; the Clearwater Dam and reservoir on the Black River in southeast Missouri; the Fall River Dam and reservoir on a major tributary of the Verdigris River in Kansas; the Addicks Dam on Buffalo Bayou in Texas; and the completion of riprap protection to the existing Denison Dam near Denison, Tex.

Each of the projects is a unit in the comprehensive plan for development of flood control on major watersheds in the Southwestern Division. Although primarily designed for flood control, many of the works are planned for multiple purposes such as production of hydroelectric power, navigation, irrigation, abatement of pollution, industrial and domestic water supply, recreation, and conservation of wildlife. The Fort Gibson project, for flood

control and hydroelectric power production, consists of a concrete dam 2,850 feet long with its crest 110 feet above the stream bed. At elevation 582 feet above sea level, top of the flood-control pool, the reservoir will have a total storage capacity of 1,287,000 acre-feet. This capacity will be divided into 922,000 acre-feet for flood control and 365,000 acre-feet for power storage.

For both flood control and hydroelectric power, the Bull Shoals Dam will provide a large reservoir for recreation and wildlife as well as benefits to navigation. The dam will be a concrete structure, an overflow spillway will be located on the right side of the flood plain, and the nonoverflow section on the left. Flows will be regulated by radial crest gates.

War Department Seeks Aid in German Industry Surveys

The United States War Department is seeking the co-operation of American industry in its investigations of German industry. The Department wishes assistance in selecting and microfilming in Germany data that may be valuable to American science and industry. Suggestions about specific information which American companies would like to have from Germany, about where valuable information might be found, and about what industries in Germany might possess information not now available are wanted.

Help also is needed in recruiting personnel for the work of searching German files. Qualified American technicians are indispensable for the job of supervision and selection. Technical men are needed in the following fields: chemicals, aeronautics, automotive, machine tools, general industrial equipment, fuels and lubricants, metals and minerals, communications equipment, scientific instruments, shipbuilding, and textiles.

A knowledge of German is essential. Appointments are subject to Civil Service approval and are made for a minimum of six months. Any industry or scientific group interested in specific German industrial methods and able to assign personnel to visit Germany should write John C. Green, executive secretary, Office of the Publication Board, Department of Commerce, Washington 25, D. C.

Arthur B. Berresford, Engineer–Doctor, Dies

Arthur Beattys Berresford, former engineer and member of AIEE, who had been practicing as a physician since 1936, died April 16, 1946, in New York, N. Y. Doctor Berresford was 42 years of age and a resident of Ithaca, N. Y. He was the son of the late AIEE Past President A. W. Berresford.

When he finished his internship in the Waterbury (Conn.) Hospital in 1936, Doctor Berresford became a general practitioner in Ithaca. From 1942 to 1944 he was a research fellow in the department of allergy of the Roosevelt Hospital, New York, N. Y. He wrote several articles on allergy and was coauthor with A. B. Sperling of the book, "Know Your Hay Fever." His article, "Musings of an Engineer–Doctor," was published in *Electrical Engineering*, June 1945, pages 212–14. Doctor Berresford held the degrees of bachelor of arts and electrical engineer, as well as his medical degree.

Electrical Engineers Needed by Army Security Agency

The Army Security Agency, Arlington, Va., reports an urgent need for graduate electrical engineers, including electronic specialists, to undertake vital research and development work. The openings have been created by demobilization of military personnel. Base pay, depending on education and engineering experience, ranges from $2,650 to above $5,000 per annum. These are Federal Civil Service appointments, with a 40-hour work week, 26 days annual leave, and 12 days sick leave.

Arlington, Va., is a suburb of Washington, D. C. Room in a private home will be reserved in advance for employees. Application should be made only by American citizens on Federal Employment Form 57 (available at all Post Offices) and forwarded to: Chief, Personnel and Training Branch, WDGSS-61, Army Security Agency, The Pentagon, Washington 25, D. C.

Veterans Request Catalogues. The Veterans Administration Construction Service, 900 North Lombardy Street, Richmond, Va., desires to receive catalogues of materials and equipment from manufacturers and jobbers, covering general building construction, electric heating, ventilating, plumbing, refrigeration, air conditioning, outside utilities, waterworks, and sewerages.

JOINT ACTIVITIES

Doctor Craver Receives Certificate. At a dinner given in his honor May 22, 1946, Doctor Harrison W. Craver, retiring director of the Engineering Societies Library, New York, N. Y., received a certificate of appreciation of his services signed by the presidents of the Founder Societies. The certificate reads:

Harrison Warwick Craver has served as director of the Engineering Societies Library from 1917 to 1946. One of his first tasks was to consolidate into a single collection the libraries of the Founder Societies which had been maintained as separate collections up to that time. He also undertook and completed over a period of years a card catalog of these combined libraries. Through the institution of translation, abstracting, photostatic, and loan services, he gave the library national scope.

His skill as a librarian, his knowledge of applied science and engineering, his sound judgment, his zeal for his work, and his unfailing courtesy have combined to provide an unequalled library service for the engineers of the nation.

In token of its appreciation, the governing body of each of the Founder Societies, whose combined libraries constitute the Engineering Societies Library, has entered this minute on its official records.

Cleveland Council Guides High School Students

For the second successive year, the Cleveland Technical Societies Council recently devoted two evening sessions to counseling high school students, with the AIEE Cleveland Section a prominent participant.

Junior and senior high school students from public, private, suburban, and parochial schools in the Cleveland area were invited to attend a meeting covering the engineering and associated professions in a general way. Later the students were divided into smaller groups which dealt with the specific fields of their interest.

The general meetings were addressed by A. T. Colwell, vice-president, Thompson Products, Inc., Cleveland, on "The Application of Fundamentals in Practical Engineering." The electrical engineering group was led by D. E. Inman (M'45) engineering and service manager in the Cleveland district for the Westinghouse Electric Corporation. The panel of counselors for the electrical group was composed of:

L. T. Blaisdell (F '39) commercial vice-president, General Electric Company; W. H. Chase (M '42) chief engineer, Ohio Bell Telephone Company; C. C. Dash (M '39) president, Hertner Electric Company; W. C. Davis (A '35) professor of electrical engineering, Fenn College; W. R. Hough (M '41) chief engineer, Reliance Electric Company; J. R. Martin (A '35) associate professor of electrical communication, Case School of Applied Science; C. N. Rakestraw (M '21) supervisor, employees training, Cleveland Electric Illuminating Company; H. P. Sherer (M '45) chief engineer, Hertner Electric Company.

Before the meetings pamphlets briefly defining the engineering profession and its various branches were distributed to the high schools. Students planning to attend were asked to fill in cards indicating the branch of engineering in which they were specially interested, the points they would like discussed, and the name of any adult who would accompany them.

In addition to the one on electrical engineering, the following discussion groups were provided: architecture, chemical engineering, chemistry, civil engineering, mechanical engineering, metallurgy, and physics. The Cleveland Council has a membership of 35 organizations.

OTHER SOCIETIES •

Quality Control Society Founded. The American Society for Quality Control was established at a meeting held February 16, 1946, in New York, N. Y., as a national society for those interested in industrial quality control. Representatives of 17 local societies organized during the war in various parts of the United States attended

Future Meetings of Other Societies

American Chemical Society. National Chemical Exposition, September 10–14, 1946, Chicago, Ill.

American Society for Testing Materials. Annual meeting, June 24–28, 1946, Buffalo, N. Y.

American Society of Mechanical Engineers. Annual meeting, June 17–20, 1946, Detroit, Mich.

American Welding Society. Annual meeting, November 17–22, 1946, Atlantic City, N. J.

Canadian Electrical Association. Annual meeting, June 26–28, 1946, Banff, Alberta, Canada.

Illuminating Engineering Society. National convention, September 18–21, 1946, Quebec, Quebec, Canada.

Instrument Society of America. Exhibit and conference, September 16–20, 1946, Pittsburgh, Pa.

International Conference on Large High-Voltage Networks. June 27–July 6, 1946, Paris, France.

National Electrical Manufacturers Association. June 17–19, 1946, Hot Springs, Va.

National Electrical Contractors Association. Annual meeting, October 14–18, 1946, Atlantic City, N. J.

National Electronics Conference. October 3–5, 1946, Chicago, Ill.

Refrigeration Equipment Manufacturers Association. Fourth refrigeration and air conditioning exposition, Cleveland, Ohio, October 29–November 1, 1946.

Television Broadcasters Association, Inc. Second conference and exhibition, New York, N. Y., October 10–11, 1946.

the first meeting. Purpose of the society will be the advancement and diffusion of knowledge of the science of quality control and its application to industrial progress. A magazine, *Industrial Quality Control*, originally published by the Buffalo, N. Y., society will be issued bimonthly. Professor Martin A. Brumbaugh of the University of Buffalo will be chairman of the editorial board. The first officers elected by the new society are:

President: George D. Edwards (M '26) director of quality assurance, Bell Telephone Laboratories, Inc., New York.

Vice-president: Andrew I. Peterson (A '23) manager of quality control, RCA Victor Division, Radio Corporation of America, Harrison, N. J.

Executive secretary: Ralph E. Wareham, manager, new products division, National Photocolor Corporation.

Treasurer: Alfred L. Davis, Rochester (N. Y.) Institute of Technology.

Valor Awards Re-established by EEI. Announcement of the reinstatement of its annual Claude L. Matthews Valor Awards, suspended during the war, has been made by the Edison Electric Institute. The awards honor "acts of devotion to duty wherein extraordinary courage has been exercised in efforts to maintain or restore important electric service in the shortest possible time." Any employee of a public utility, either publicly or privately owned, is eligible for the first postwar award, provided his deed of valor was performed during the calendar year of 1946. This is a departure from prewar practice as previously only employees of privately owned companies were considered. Recommendations for the awards must be made by the chief executive of a company and must be forwarded to the secretary of the Edison Electric Institute not later than April 1, 1947. Three cash awards of $150 are made, and an appropriate lapel emblem and citation accompanies each.

Fire Protection Association Observes 50th Anniversary

With its annual meeting in Boston, Mass., June 3–7, 1946, the National Fire Protection Association celebrates 50 years as international clearing house for authoritative information on the subject of fire protection and fire prevention. The association, which was established in Boston in 1896 as a noncommercial, nonprofitmaking organization, today includes more than 150 national organizations and 10,000 individuals in 37 countries in its membership. Although the majority of its members are recruited from industry, membership is open to any individual or organization interested in the protection of life or property from fire.

During the 50 years of its existence, a prime function of the NFPA has been to provide nearly 150 technical standards and other popular and technical literature in the field of fire waste control. Since 1923 the association has maintained a field service to make direct contact with states, provinces, and cities throughout the United States and Canada. The work of NFPA engineers is recognized as an influential factor in the establishment of techniques and practices which have reduced loss of life and destruction of property by fire. Among the most important developments in NFPA history was the establishment, in 1933, of the *Volunteer Firemen Magazine* (now *Firemen*) in an effort to reach the many small communities which are protected by volunteer fire departments.

One of the most recent and significant services rendered by the NFPA was occasioned by World War II. This war, unlike any previous war, was marked by the extensive use of fire as a devastating weapon, and thus the association, through its experience and knowledge of fire, was able to contribute much to the development of weapons for offensive warfare by the United States.

ASTM Moves to New Headquarters. The American Society for Testing Materials has moved its headquarters from 260 South Broad Street, Philadelphia, Pa., to its permanent headquarters building at 1916 Race Street, Philadelphia 3. The new building, which was purchased and remodeled through contributions made by many of the companies and individuals active in the society's work, provides additional space required by the expansion of the society's staff.

Howes and Gilson Appointed By Canadian Engineers' Council

Appointment of Doctor F. S. Howes as chairman and W. J. Gilson (M '38) as vice-chairman has been announced by the Canadian Council of Professional Engineers and Scientists, which was formed in 1945.

The Council is composed of the presidents or their alternates of 11 national scientific professional engineering societies in Canada and is the result of four or five years of discussions among interested groups. As it is organized as a Canadian District, the AIEE has been included in the Council. The Council deals on a national scale with such matters of general interest to engineers and scientists as economic status, postwar planning projects, and matters connected with the development of Canadian resources. After one year of operation the Council reports a considerable measure of success in its dealings with the Dominion Government.

Doctor Howes is a consulting radio engineer and an assistant professor of electrical engineering at McGill University, Montreal, Quebec, from which he was graduated with honors in 1924. His graduate studies were completed at the University of London and the University of California. He is member of the Institute of Radio Engineers and the Corporation of Engineers of Quebec. A biography of Mr. Gilson who is a former vice-president of AIEE may be found on page 129 of the March 1943 issue of *Electrical Engineering*.

Besides AIEE, the bodies represented in the Council are: the Dominion Council of Professional Engineers, the Canadian Institute of Mining and Metallurgy, the Chemical Institute of Canada, the Royal Architectural Institute of Canada, the Canadian Society of Forest Engineers, the Agricultural Institute of Canada, the Dominion Council of Federated Professional Employees, the Canadian Institute of Surveying, the Canadian Association of Professional Physicists, and the Canadian Council of the Institute of Radio Engineers.

Conference on Insulation Plans Meeting for November

The conference on electrical insulation of the National Research Council, after five years of relative inactivity, has announced that preparations are being made for a three-day meeting at the Johns Hopkins University, Baltimore, Md., November 7–9, 1946.

The last meeting of the conference, its 14th annual meeting, was held in 1941, and at that time Ward F. Davidson (F '26) director of research, Consolidated Edison Company of New York, Inc., was appointed to continue as conference chairman. Mr. Davidson had been chairman since 1939. Other members of the executive committee of the conference are:

S. O. Morgan, *vice-chairman;* Thorstein Larsen (A '34) *secretary;* C. L. Dawes (F '35); W. A. Del Mar

(F '20); R. N. Evans; C. F. Hill (F '39); F. L. Miller; H. H. Race (F '39); Arthur von Hippel (M '37); and John B. Whitehead (F '12).

Those desiring to receive copies of the detailed program and other notices are requested to send their names and addresses to Mr. Davidson.

EDUCATION

Yale Electrical Engineering Fellowship. An annual fellowship, to be known as the Westinghouse Fellowship in Electrical Engineering has been established at Yale University, New Haven, Conn. The fellowship will be open to all candidates holding a bachelor of science degree in electrical engineering from a college or university in the United States. The recipient will be chosen by the faculty of the Yale University department of electrical engineering. The first fellowship has been awarded to James A. M. Kelly who was graduated from Yale University in 1942 and who for the past three years has been doing research in the United States Naval Research Laboratory, Washington, D. C.

Westinghouse Fellowship at Illinois. Announcement of the establishment of a graduate fellowship in power systems engineering at the Illinois Institute of Technology by the Westinghouse Educational Foundation, has been made by Doctor Louis T. Rader (M '43) chairman of the institute's department of electrical engineering. The fellowship has been established on a yearly basis for five years. Final decision on the 1946 applicant will be made by June 16 by a joint committee representing both the foundation and the institute. In the case of veterans receiving Government allotments, the committee reserves the right to divide the fellowship between two candidates, while the Government would pay tuition fees. Ordinarily the fellowship provides a stipend of $1,500 with all tuition fees paid for 12 months of study leading to a degree of master of science in electrical engineering. The successful candidate will devote full time to the program's study of the technical problems of power generation, transmission, and distribution.

INDUSTRY

New Materials for Permanent Magnets Announced

Five new permanent-magnet materials, known as cunico, cunife, vectolite, alnico 12, and silmanal, have been announced by the General Electric Company. These new materials have many applications in the manufacture of aircraft instruments and products for which small lightweight magnets formed in intricate shapes are required.

Cunico is an alloy of copper, nickel, and cobalt. Magnets made from it are furnished only in their final shapes, because they are age-hardened in the manufacturing process. Cunico is malleable, ductile, and machinable.

Cunife is a copper-nickel-iron alloy which has all the physical properties of cunico, differing in that it has directional properties and must be magnetized only along the direction in which the material has been cold-worked, to obtain highest magnetic quality.

Vectolite is the first nonmetallic, nonconducting magnet material ever made. It is a hardened sintered combination of iron rust and cobalt oxide, mixed when still in powder form. Vectolite magnets are extremely light, being nonmetallic, and their nonconductive properties prevent electrical losses caused by conduction of current. In addition, they have a high resistance to demagnetizing forces.

Alnico 12 is made up of aluminum, nickel, cobalt, iron, and titanium. Magnets made from this material can be used in such applications as tachometer generators and electronic devices.

Silmanal has a high intrinsic coercive force, which makes magnets made from it useful in instruments where service in strong electric fields is required. Silmanal is ductile and malleable.

Electronic Heat Seals Many Consumer Products

The wartime promise that plastic fabrics would be sealed electronically in the manufacture of civilian goods now is being realized, Wiley D. Wenger, engineer of the Radio Corporation of America, recently stated at the annual spring meeting of the Society of the Plastics Industry.

Industry now is using electronic power in the fabrication of dress shields, bathing caps, raincoats, shower curtains, and many other thermoplastic products, he revealed.

A major advantage of electronic techniques, Mr. Wenger said, is that the high-frequency electric energy employed is not converted into heat until after it enters the work material. The metal electrodes used to apply the energy remain cool, while the heat generated is concentrated at the interface of two pieces of material, where it is wanted, and the degree and interval of heating can be closely controlled.

Since the electrodes themselves can be used to apply pressure, the three essentials of heat sealing—uniform heating of the surfaces to be joined, uniform pressure, and uniform cooling—can be accomplished simultaneously with a single operation.

A number of electronic heat-sealing installations saw service during the war in the production of such vital military requirements as solar stills, Wenger said, and the use of electronic equipment and techniques in this field has increased rapidly. The products involved range from ping pong balls and beach play balls to belts, button hole reinforcements, bibs, and baby pants.

A long-electrode bar sealer can be used either to produce a single seam as long as 48 inches at one shot for large articles, such as raincoats or shower curtains, or to seal several smaller objects, such as tobacco pouches. Another machine employs roller electrodes, which apply power and feed material through the machine at the same time, making a continuous seam of any length or contour.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Glass and Marble Measuring Instrument

To the Editor:

The picture of the "original a-c–d-c instrument" which appeared on page 80 of the February issue of *Electrical Engineering*, interested me especially, as I had the picture taken, having found it among the old laboratory junk, while I was in charge of instrument development at the Westinghouse company.

The caption is not quite correct, as this type of instrument was never used for alternating current, having been acquired by George Westinghouse in connection with his purchase of the Waterhouse arc lighting system in order to get into the electric lighting business on a competitive basis. When he introduced the a-c system in connection with the Gaulard and Gibbs system of transformers, Phillip Lange, Doctor C. F. Scott, and others developed what they called the "glass and marble" instrument line which comprised a long bunched wire solenoid, mounted in a glass show case type of cover, on a marble base (Figure 1). This was in the year 1888—a year also famous for the introduction of the Shallenberger meter for a-c ampere-hours, and the great blizzard.

Both indicating instruments mentioned

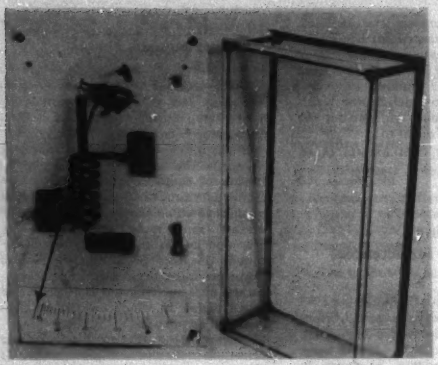


Figure 1.

operated with gravity control. Though the Waterhouse type would work after a fashion on alternating current, its inductance and the eddy current effects were too much for successful a-c operation.

It is interesting to note that in those days most designers did not think that either springs or permanent magnets were sufficiently reliable for measuring work—at least until Weston brought out his first d-c moving coil instrument—also in 1888.

PAUL MacGAHAN (F '42)

(Consulting electrical engineer, Woodstock, N. Y.)

Engineering Terminology

To the Editor:

Paul MacGahan's letter in the February issue of *Electrical Engineering*, objecting to the proposed use of the word "icon" to designate an insulated conductor, meets with my hearty approval. Apart, however, from mentioning its possible confusion with "iconoscope," a more or less legitimate application of the generic term, I have no desire to enter this controversy and shall let the contestants settle it between themselves.

I hope Mr. MacGahan's luck is better than mine in the protest against preemption of terms already recognized in other fields. My voice was raised against adoption of the term "oscilloscope" to designate the stabilized cathode-ray oscillograph, when the word already had been applied in British practice to an entirely different instrument. (Discussion by P. A. Borden of "The Oscilloscope," Frederick Bedell, Herbert J. Reich. AIEE *Transactions*, 1927, volume 46, page 550.) My appeal fell upon deaf ears; and the word now has its place in the "Standard Definitions of Electrical Terms."

Again, my protest against abuse of the noun "potentiometer" to designate a certain type of rheostat has been insistent and unremitting; and, while this example of technical slang does not yet seem to have appeared in recognized electrical standards, it is creeping into the dictionaries, and is rapidly finding a place in electrical literature—especially in the field of electronics—and in patents. So I suppose it will be but a matter of time until we reactionaries must bow to the inevitable and recognize this further short cut in the use of technical English.

PERRY A. BORDEN (F'44)

(Patent engineer, The Bristol Company, Waterbury, Conn.)

Electrical Essays

To the Editor:

With respect to my electrical essay on page 159 of the April 1946 issue of *Electrical Engineering* discussing the sudden paralleling of a capacitor C charged to a voltage E with another equal but uncharged capacitor, it is evidently incorrect to assume that a final rest condition can be reached without loss of energy. In order to analyze this problem, either the resistance or the inductance may be neglected but not both.

Qualitatively the situation is seen most clearly if the resistance is neglected, but a definite amount of series inductance is assumed to be present, in which case the charge will oscillate from one capacitor to the other indefinitely. Decreasing the inductance to a smaller value merely increases the frequency of oscillation.

At a particular instant when the charge is equally divided between the capacitors, there will be an amount of energy stored in the inductance exactly equal to that stored in the capacitors. To attain equilibrium there must be a means of losing energy, such as a resistance which will serve to damp out the oscillation and absorb the excess energy over the steady-state condition.

A quantitative solution is obtained rather easily by assuming a definite series resistance R in the circuit and neglecting the inductance. The equation for the current flow at any time is the well-known exponential:

$$i = \frac{E}{R} e^{-\frac{2t}{RC}}$$

remembering that the combined capacitance of the two capacitors in series is $C/2$.

The total energy loss in the resistance is calculated as follows:

$$W_r = \int_0^\infty Ri^2 dt = \frac{E^2}{R} \int_0^\infty e^{-\frac{4t}{RC}} dt = {}^1/_4 CE^2$$

Thus, it turns out that this loss is independent of the value of the resistance. It may be seen that as the resistance is decreased toward zero, the initial value E/R of the transient current becomes extremely high. In the more complicated case of a damped oscillation with inductance present, the resistance loss must be the same.

W. M. LEEDS (M '38)

(Manager, circuit breaker development section, Westinghouse Electric Corporation, East Pittsburgh, Pa.)

To the Editor:

The electrical essay for April illustrates the danger of setting up a "theoretical" problem without considering whether the conditions are theoretically justifiable. The fallacies in the problem as stated lie in assuming (1) the inductance of the circuit may be neglected, (2) a condition of static equilibrium will be attained.

NORTON SAVAGE (A '41)

(Engineering assistant, Federal Telephone and Radio Corporation, Clifton, N. J.)

To the Editor:

Referring to the electrical essay in the April issue, my practical comment is: Why assume the impossible? However, if the assumption of the impossible is permissible, why not consider what happens when a capacitor discharges through a circuit of negligible inductance and resistance? In this case the entire energy stored in the capacitor disappears, not one half.

The only realistic way to consider a situation of this sort is to treat it as a limiting case of vanishingly small resistance and inductance. This method explains the result correctly. As is done in the essay, I use circuit theory, not field theory, which is not entirely correct.

WALDO V. LYON (F '33)

(Professor of electrical machinery, Massachusetts Institute of Technology, Cambridge, Mass.)

To the Editor:

Referring to the electrical essay in the April issue, the fallacy in the statement of the problem resides in the assumption that, if the resistance in circuit between the two capacitors is negligible, the energy dissipated in that resistance will be negligible. The expression for the rate of dissipation of energy in a resistance across which is impressed a given potential is E^2/R which varies inversely with the resistance.

J. LESTER WOODBRIDGE (F '21)

(Patent department, Electric Storage Battery Company, Philadelphia, Pa.)

To the Editor:

I read with interest your electrical essay in the April issue. I would like to propose a corollary. Since the resistance and induction are negligibly small, the circuit will oscillate at infinite frequency for an infinite time. This will make a good perpetual motion radar set.

OTTO J. M. SMITH (A '42)

(Research Laboratory, Scranton Record Company, Scranton, Pa.)

To the Editor:

The electrical essays which appear from time to time in *Electrical Engineering* teach a strong lesson against the complete reliance on intuition in the solution of engineering problems. It is hoped that this department will be continued, not only for the recreation that it offers, but for its educational value in electrical fundamentals.

W. B. CONOVER (A '42)

(Works laboratory, General Electric Company, Pittsfield, Mass.)

To the Editor:

The law of conservation of energy always holds—even in the case of the electrical essay published in April 1946—as long as all the circuit parameters are included.

The resistance of the circuit is never so negligibly small that considerations of energy lost, especially in a transient circuit, may be tossed out the window.

No fair, gentlemen—include the resistance, put the heat back on, and let the energy dissipate as it ought to.

STANLEY C. MARSHALL (A '44)

(Editor of technical publications, Sauerman Brothers, Inc., Chicago, Ill.)

System of Graphing Capacities and Inductances

To the Editor:

A letter to the editor in the December 1945 issue of *Electrical Engineering*, page 469, brings to mind a simple precise system of graphing capacities and inductances, at the same time indicating impedance, as shown in Figure 1. Used in conjunction with Keuffel and Esser Company sheet number 359–47, values of all inductances and capacities with their impedances are obtained easily and precisely.

A. S. RUNCIMAN (M '35)

(Superintendent, Shawinigan Water and Power Company, Montreal, Quebec, Canada)

An Analysis of Electromagnetic Forces

To the Editor:

In the October 1945 issue of *Electrical Engineering* you published an article by W. A. Tripp titled "An Analysis of Electromagnetic Forces."

In this article the author criticizes the concept of the attraction of two parallel currents of equal direction, because two streams of electrons in parallel motion of equal velocity (which represent two parallel currents) cannot attract each other due to their velocity, as they have no relative motion. He then postulates new laws of nature governing electromagnetic phenomena and cites the observed constrictions of molten metals in which current flows as proof of these theories.

However, the attraction of two streams of electrons in parallel motion can be derived from electrostatics using the formulas of special relativity. Proof of this also will contain the answer to the author's question: "If parallel currents attract each other, why was the attraction of parallel electron streams never observed"? It also will explain the constriction of molten metals by passing direct currents.

Let us consider a co-ordinate system *S*

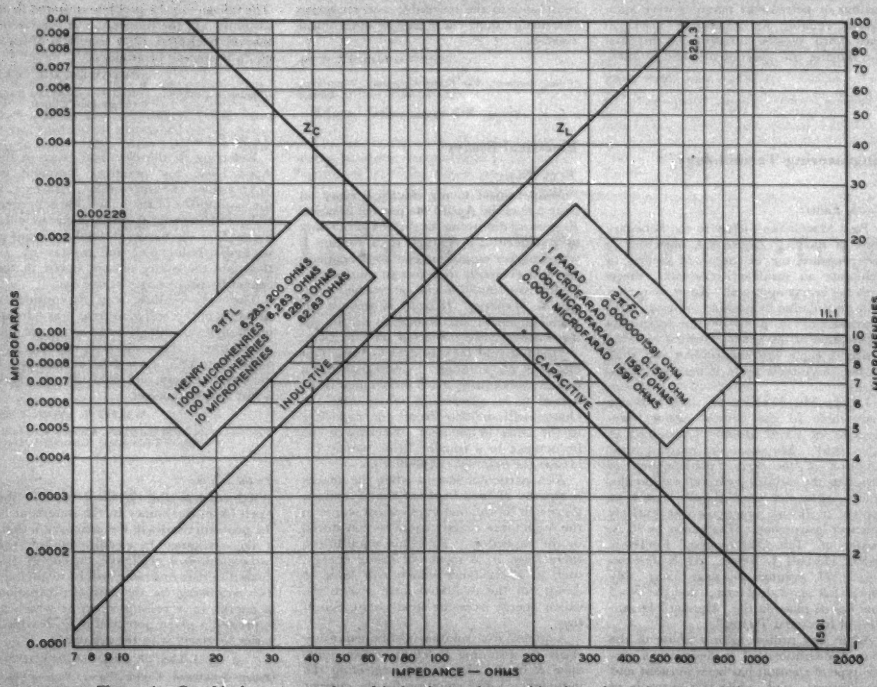


Figure 1. Graphical representation of inductive and capacitive impedance for F=1,000 kilocycles

and another one S^*. The origin of the co-ordinate system S^* is moving along the x axis of the co-ordinate system S in the positive x direction with a uniform velocity v. Then, if we use letters with an asterisk for all values which an observer at rest in co-ordinate system S^* measures, and letters without an asterisk for the values measured by an observer at rest in co-ordinate system S, the equations of transformation between the two sets of measurements are (using the formulas of special relativity for particles at rest in co-ordinate system S^*):

$$F_x = F_x^* \qquad \text{force in the } x \text{ direction} \qquad (1)$$

$$F_y = F_y^* \sqrt{1-\frac{v^2}{c^2}} \qquad \text{force in the } y \text{ direction} \qquad (2)$$

$$F_z = F_z^* \sqrt{1-\frac{v^2}{c^2}} \qquad \text{force in the } z \text{ direction} \qquad (3)$$

$$x^* = \frac{x-vt}{\sqrt{1-\frac{v^2}{c^2}}} \qquad (4)$$

$$y^* = y \qquad (5)$$

$$z^* = z \qquad (6)$$

$$t^* = \frac{t-\frac{vx}{c^2}}{\sqrt{1-\frac{v^2}{c^2}}} \qquad (7)$$

where c is the velocity of light.

We assume now two charges, q_1 and q_2 at rest in the co-ordinate system S^*

q_1 at $x^* = 0 y^* = a$
and q_2 at $x^* = b y^* = 0$

By Coulomb's law the forces on q_1 measured by an observer at rest in the co-ordinate system S^* are

$$F_x^* = -\frac{q_1 q_2 b}{(b^2+a^2)^{3/2}} \qquad (8)$$

$$F_y^* = \frac{q_1 q_2 a}{(b^2+a^2)^{3/2}} \qquad (9)$$

$$F_z^* = \phi \qquad (10)$$

There are no other forces measured by an observer at rest in the co-ordinate system S^*, as for him the charges are stationary. Now we shall consider what an observer at rest in co-ordinate system S is measuring. For him there are two charges moving with constant velocity in the $+x$ direction. To get the forces measured by this observer we must use the relativistic transformations equation 1 divided by equation 7 on equations 8, 9, and 10. As all forces are independent of time we set arbitrarily $t = \phi$ and get

$$\left(\text{with } \beta = \sqrt{1-\frac{v^2}{c^2}}\right) x^* = \frac{x}{\beta} \qquad (4a)$$

$$F_x = \frac{-q_1 q_2 b}{\beta\left(\frac{b^2}{\beta^2}+a^2\right)^{3/2}} \qquad (11)$$

$$F_y = \frac{q_1 q_2 \beta a}{\left(\frac{b^2}{\beta^2}+a^2\right)^{3/2}} \qquad (12)$$

$$F_z = \phi \qquad (13)$$

To get the force of a current in the $+x$ direction on a current element we replace q_2 by a line charge

$$\sigma dx = \sigma^* dx^* = q_2 \qquad (14)$$

at rest in co-ordinate system S^*. Substituting equation 14 in equation 12 and observing that b is now the independent variable, we integrate from

$x = -\infty$ to $x = +\infty$ and get ($b \equiv x$)

$$F_x = -\int_{-\infty}^{+\infty} \frac{q_1 \sigma x dx}{\beta\left(\frac{x^2}{\beta^2}+a^2\right)^{3/2}} = \phi \qquad (15)$$

$$F_y = \int_{-\infty}^{+\infty} \frac{\beta q_1 \sigma a dx}{\left(\frac{x^2}{\beta^2}+a^2\right)^{3/2}} = \frac{2q_1\sigma\left(1-\frac{v^2}{c^2}\right)}{a} \qquad (16)$$

$$F_z = \phi \qquad (17)$$

We now divide equation 16 in two parts

$$F_y = F_{1y} + F_{2y} = \frac{2q_1\sigma}{a} - \frac{2q_1\sigma v^2}{ac^2} \qquad (17)$$

F_{1y} is the electrostatic repulsion of the line charge σ on q_1 and F_{2y} is a force *due to the relative motion of the observer and the charges*. Note that the charges do not move relative to each other.

We now shall transform F_{2y}.

$$F_{2y} = \frac{2q_1\sigma v^2}{ac^2} = \frac{2}{a}\cdot\frac{q_1 v}{c}\cdot\frac{v\sigma}{c} \qquad (18)$$

In equation 18 all charges are in absolute electrostatic units. If we use absolute electromagnetic units, we must multiply each charge by c and get

$$F_{2y} = -\frac{2}{a}\frac{q_1^{(esu)} v}{c}\cdot\frac{\sigma^{(esu)} v}{c} = -\frac{2}{a} q_1^{(emu)} \times {}_{v,\sigma}{}^{(emu)} v \qquad (19)$$

where

esu = electrostatic units
emu = electromagnetic units

As charge density velocity gives current and charge velocity gives one current element

$$q_1^{(emu)} v = i_1 ds^{(emu)} \qquad (20)$$

$$\sigma^{(emu)} v = i_2^{(emu)} \qquad (21)$$

introducing equations 20 and 21 in equation 19 we get:

$$F_{2y} = -\frac{2 i_1 i_2 ds}{a} [emu] \qquad (22)$$

As equation 22 is derived without reference to a conductor, it is proof of the existence of an attraction of two parallel currents without influence of conducting material.

The reason that attraction of parallel electron streams in free space never has been observed is that electromagnetic forces are by their very nature much smaller than electrostatic forces. (The electromagnetic attraction is only $a(v/c)^2$ part of the electrostatic repulsion of the two moving electron streams.)

Only in the case of the current inside a conductor the electromagnetic attraction can be measured, because the electrostatic forces of the conduction electrons are neutralized by the positively charged stationary atoms which are in close proximity to the moving electrons.

Although there exists a force which tends to crowd a direct current towards the center of a wire, this force is counteracted by the electrostatic forces developed between the positively charged atoms of the conductor and the electrons. This force limits any crowding to very small values.

In the case of a molten metal through which a direct current flows, the atoms are not fixed in position, and therefore can move simultaneously with the electrons under the influence of the electromagnetic forces and produce a crowding of the molten metal toward the axis of the current.

APPENDIX. DERIVATION OF INTEGRAL OF EQUATION 16

$$\int_{-\infty}^{+\infty} \frac{\beta q_1 \sigma a dx}{\left(\frac{x^2}{\beta^2}+a^2\right)^{3/2}}$$

$$= \frac{\beta q_1 \sigma}{a^3} \int_{-\infty}^{+\infty} \frac{dx}{\left(\frac{x^2}{a^2\beta^2}+1\right)^{3/2}}$$

$$= \frac{\beta q_1 \sigma}{a^3} \int_{-\infty}^{+\infty} \frac{a\beta dy}{(y^2+1)}$$

$$= \frac{\beta^2 q_1 \sigma}{a} \int_{-\infty}^{+\infty} \frac{dy}{(y^2+1)^{3/2}}$$

where

$$y = \frac{x}{a\beta}$$

$$y^2 = \frac{x^2}{a^2\beta^2}$$

$$dy = \frac{dx}{a\beta}$$

$y = \infty \ldots x = \infty$
$y = -\infty \ldots x = -\infty$

and equals

$$\frac{\beta^2 q_1 \sigma}{a} \int_{-\infty}^{+\infty} \frac{\cosh \alpha d\alpha}{\cosh^3 \alpha d\alpha}$$

$$= \frac{\beta^2 q_1 \sigma}{a} \int_{\alpha=-\infty}^{\alpha=+\infty} d(\tanh \alpha) = \frac{\beta^2 q_1 \sigma}{a} \cdot 2$$

where

$y = \sinh \alpha$
$dy = \cosh \alpha d\alpha$
$(\sinh^2 \alpha + 1)^{1/2} = \cosh \alpha$

$y = \infty \ldots \alpha = \infty$
$y = -\infty \ldots \alpha = -\infty$

I hope that the foregoing lines, although they bring no material not previously known, will clarify the nature of electromagnetic attraction of currents to those to whom this concept is not entirely clear.

ALFRED GRONNER

(Montevideo, Uruguay)

NEW BOOKS • • •

"Extinguishing and Alarm Equipment (National Fire Codes, volume 4, 1946 edition)." This edition of the National Fire Codes increases to 47 the standards dealing with automatic sprinklers and water supply, fire extinguishers, municipal and rural fire apparatus, watchman service, and other related features of supervision and maintenance. Suggesting measures providing reasonable safety without undue expense or inconvenience, in general these standards specify the methods of installation but do not attempt to rule as to the conditions under which the several kinds of protection should be provided. This volume supersedes the edition of 1943. All the codes are in the form of suggested ordnances, standards, or recommended good practice requirements and are recognized as authoritative guides to the best practices. The National Fire Protection Association, Boston 10, Mass., 1946. 735 pages, cloth, $3.

The following new books are among those recently received at the Engineering Societies Library. Unless otherwise specified, books listed have been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books in question.

SYMPOSIUM ON MAGNETIC PARTICLE TESTING. American Society for Testing Materials, 260 South Broad St., Philadelphia, Pa., 1945. 122 pages, illustrated, 9 by 6 inches, paper, $1.25. Eight papers by authorities and two tentative methods for testing are contained in this symposium. Topics covered by the articles include the equipment, specifications, and procedure for magnetic particle inspection; the application of the method to the testing of aircraft parts; and the inspection of castings and forgings.

VORLESUNGEN ÜBER DIFFERENTIAL GEOMETRIE UND GEOMETRISCHE GRUNDLAGEN VON EINSTEINS RELATIVITÄTSTHEORIE. Volume I, Elementare Differentialgeometrie. By W. Blaschke. Third edition, prepared by G. Thomsen, published by Dover Publications, New York, N. Y., 1945. 322 pages, illustrated, 8¾ by 5½ inches, cloth, $3.50. Essentially a textbook of differential geometry in a Euclidean space of three dimensions, this volume provides also an introduction to original research in the field. The following is a partial table of contents: Introduction-vectors; theory of curves; elements of the theory of surfaces; invariant derivatives on a surface; geometry on a surface; problems of surface theory in the large; extremal properties of curves and surfaces; line geometry. Particular emphasis is placed on the relations between differential geometry and the calculus of variations.

RELAY ENGINEERING. By C. A. Packard. Struthers-Dunn, Philadelphia, Pa., 1945. 640 pages, illustrated, 7 by 4½ inches, fabrikoid, $3. Following an introductory and historical opening chapter are 50 pages devoted to definitions of terms and illustrations with code designations of some 100 magnetic structures manufactured by the company issuing the manual. Succeeding chapters deal with description of relays and auxiliary equipment, applications and circuits, the selection of relays for specific tasks, installation and service work, and standards. A bibliography and an appendix of technical data are provided.

POLAR MOLECULES. By P. Debye. Dover Publications, New York, N. Y., 1945. 172 pages, illustrated, 8¾ by 5½ inches, cloth, $3.50. A survey is presented of the questions which arise in connection with the conception of polar molecules as systems having a distribution of electric charges which can be characterized by a permanent electric moment. The treatment is comprehensive, and the introduction of quantum theory makes it possible to develop in detail the connection between polarity and the phenomena of dispersion and absorption, especially in the infrared.

DEVELOPMENT OF MATHEMATICS. By E. T. Bell. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1945. 637 pages, 9 by 5¾ inches, cloth, $5. Although this book covers the evolution of mathematics from about 4000 B.C. to the present day, it is not strictly a history. The author's intent is rather to indicate main trends over this period, presenting them only through typical major episodes in each. Chief principles, methods, and theories are considered in both pure and applied mathematics. The author clearly shows how seemingly unimportant phases have been developed into useful lines of endeavor.

AUTOBIOGRAPHY OF SCIENCE. Edited by F. R. Moulton and J. J. Schifferes. Doubleday, Doran and Company, Inc., Garden City, N. Y., 1945. 666 pages, tables, 8¼ by 5½ inches, cloth, $4. From the time of the earliest records to the 20th century, the great triumphs of science in all fields are recorded in this volume in the original words of those who achieved them. The introductory notes by the authors immediately preceding the separate items provide brief information about the lives, activities, and achievements of the men whose writings are presented. This unusual collection will be of interest to those who like their information firsthand, allowing for the necessity of translation from foreign languages.

AUFGABEN UND LEHRSATZE AUS DER ANALYSIS. Volume I. Reihen, Integralrechnung Funktionentheorie. 342 pages. Volume 2. Funktionentheorie, Nullstellen, Polynome, Determinanten Zahlentheorie. 412 pages. By G. Polya and G. Szego. Dover Publications, New York, N. Y., 1945. Tables, 8¼ by 5½ inches, cloth, $3.50 each volume. The purpose of this text is to present not merely a collection of problems but an arrangment of the problems in such order and grouping as will cultivate good habits in the mathematical thinking of the student. Accordingly the two volumes cover the following topics in the field of mathematical analysis as follows: Volume I, infinite series and sequences; integral calculus; functions of a complex variable-general part. Volume II, functions of a complex variable-special part; location of zeros; polynomials; determinants and quadratic forms; number theory.

ART OF PLAIN TALK. By R. Flesch, foreword by L. Bryson. Harper and Brothers, New York, N. Y., and London, England, 1946. 210 pages, tables, 8¼ by 5 inches, cloth, $2.50. Two years ago Mr. Flesch published his doctor of philosophy dissertation, "Marks of Readable Style." This book is a less formal presentation of the subject matter. It is not a book on basic English. Scientific studies of readability have produced a formula based on sentence length, and on the number of affixes and personal references included. The main feature of this book is this formula which is intended only as a yardstick. However, readers are warned not to allow the rules and computations to obscure the principles of plain English. Examples of difficult material rewritten in simple English are included.

BUILDING AN ENGINEERING CAREER. By C. C. Williams. Second edition, revised. McGraw-Hill Book Company, New York, N. Y., and London, England, 1946. 309 pages, illustrated, 8¼ by 5½ inches, cloth, $2.50. An orientation course for freshmen engineers. The author discusses what engineering is and how to study it, gives something of its historical background, and calls attention to modern achievements.

PAMPHLETS • • •

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquiries should be addressed to the issuers.

Movies Go to Work. Bell and Howell Company, 7100 McCormick Road, Chicago 45, Ill., 23 pages.

Public Domain. A new weekly digest of expiring patents published by the Scientific Development Corporation, 614 West 49th Street, New York 19, N. Y. Charter subscriptions for one year, $45; for six months, $25; for ten weeks, $10; 250 pages.

A Dynamic Equipment Policy for America. Machinery and Allied Products Institute, 221 North La Salle Street, Chicago, Ill. Single copies, 25 cents; 5 to 24 copies, 15 cents each; 25 copies or over, 10 cents each; 26 pages.

How to Buy Surplus Machine Tools. National Machine Tool Builders' Association, 10525 Carnegie Avenue, Cleveland 6, Ohio, 21 pages.

The Foreman and the Veteran. By Ted Handelman. National Foreman's Institute, Inc., Deep River, Conn., 32 pages, 25 cents, subject to quantity discount.

What's Ahead for the Veteran. By Ted Handelman. National Foremen's Institute, Inc., Deep River, Conn., 22 pages, 15 cents, subject to quantity discount.

Publicity for the Small Company. By James W. Corey. National Electrical Manufacturers Association, 155 East 44th Street, New York 17, N. Y. Copies may be obtained at cost.

Airport Electrical Equipment. Westinghouse Electric Corporation, P. O. Box 868, Pittsburgh 30, Pa.

Protection of Electric Circuits and Machines. By C. F. Hedlund, A. L. Brown. Associated Factory Mutual Fire Insurance Companies, Inspection Department, 184 High Street, Boston 10, Mass., 72 pages, $2.

Production Moves Ahead. By the Director of War Mobilization and Reconversion. Bureau of Special Services, Bureau of the Budget, 1400 Pennsylvania Avenue N. W., Washington, D. C., 56 pages.

The Tin Research Institute 1942–1944. A report of the work of the Institute, its current researches, and their bearing on future developments. Fraser Road, Greenford, Middlesex, England. Represented in the United States by: Battelle Memorial Institute, 505 King Avenue, Columbus, Ohio, 32 pages.

Vickers, Rockwell, and Brinnell Hardness Values for Various Materials and Alloys. A chart. Prepared by J. T. Agnew. Engineering Experiment Station, Purdue University, Lafayette, Ind.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

The Polyphase Commutator Regulator for Speed Control

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Synopsis: This paper presents an explanation of the theory and explains the characteristics of an a-c adjustable-speed drive obtained by using a polyphase commutator regulator mechanically coupled to the shaft of a wound-rotor induction motor and electrically connected to its slip rings. The theoretical loci of the system current vectors with respect to the voltage vectors of the induction motor are developed in terms of the constants of the machines and the applied voltage. A method of determining the characteristics of the drive from no-load tests or from design data is presented. The characteristics predicted on these bases are in excellent agreement with those obtained experimentally.

SEVERAL methods have been employed to provide an a-c drive of large capacity with suitable adjustable-speed characteristics. The choice of the method used usually is dependent on the characteristics required by the load. One of the most satisfactory of these systems from the standpoint of speed control is obtained by supplying the primary of an induction motor from a balanced polyphase system and connecting its slip rings to a shunt-connected polyphase commutator regulator (see Figure 1).

The electrical circuit of the rotor of this regulating machine is similar to that of a d-c armature. It usually is designed for low voltage in order to obtain good commutation of the alternating currents supplied to it from the brushes. The spacing of the brushes on the commutator is determined by the number of phases on the motor rotor, that is on a 3-phase machine the angle between brushes is 120 electrical degrees. The stator or field winding of the regulator may be a normal distributed polyphase winding such as that found on a polyphase induction motor. However, for good commutation the main field windings usually are placed on salient poles between which interpoles can be provided. A compensating winding usually is placed on the stator and connected in series with the rotor or armature. The field may be designed for operation either in series or in shunt with the armature. The drive using the shunt connection is the more common and is the one which is discussed here. This connection is shown diagrammatically in Figure 1. A transformer bank normally is provided to control the voltage applied to the field winding and thereby control the speed. Excellent speed regulation can be obtained when shunt excitation of the regulator is employed. This drive is a constant horsepower device. For a given power input the torque available at the shaft is increased as the speed is adjusted to lower values.

The object of this paper is

(*a*). To develop the theory of operation of the adjustable-speed drive consisting of a wound-rotor induction motor and a shunt-connected polyphase commutator regulator.

(*b*). To obtain the expression for the primary current of the induction motor as a function of the phase voltage, the machine constants, and the slip.

(*c*). To present a method of predicting the characteristics of the drive from no-load readings taken experimentally on the machines, or from the design data of the machines employed.

Theory

When the stator, or field, winding of the polyphase commutator regulator is connected to a balanced polyphase supply, a rotating magnetic field is set up which induces a voltage in this winding which is essentially equal and opposite to the applied voltage. A voltage is induced in the conductors of the rotor also, unless it is rotating at synchronous speed in the same direction as the magnetic field. If the rotor is stationary the voltages in these conductors can be measured between brushes placed on the commutator. By proper distribution of these brushes on the commutator, these voltages can be made to form a balanced polyphase system of any desired number of phases. If the brushes are all shifted in one direction in unison, the voltages between them are unchanged in magnitude, but the time phase of these voltages with respect to the field voltage will be changed. In this way the time phase of the brush voltages may be so shifted that they directly oppose the voltages supplying the field, or the voltages normally supplied to the brushes. This is referred to as the zero

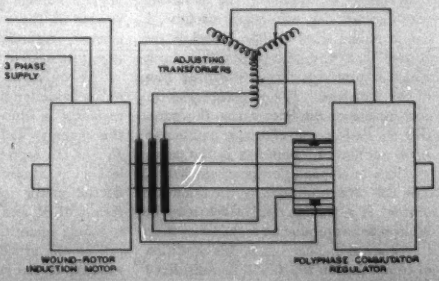

Figure 1. Complete circuit diagram of adjustable-speed drive

Paper 46-39, recommended by the AIEE committee on electric machinery for presentation at the AIEE winter convention, New York, N. Y., January 21-25, 1946. Manuscript submitted August 21, 1945; made available for printing December 4, 1945.

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brush position. If the effective turns ratio between the field and the armature is unity, that is, a given value of flux induces voltages of equal magnitude in both field and armature, and if the brushes are in the zero position, the voltage which appears at the brushes is equal and opposite to the voltage on the induction motor slip rings at standstill, which is the voltage applied to the stator winding of the commutator machine.

If the stator of the regulator is supplied with balanced alternating voltages, and the armature is rotated at some speed, N, with the brushes not connected to the line, the voltage appearing between them is still of the frequency applied to the field. The armature is divided into groups of conductors between adjacent brushes. Although at different instants different conductors may comprise these groups due to the rotation of the armature, nevertheless, the group as a unit is stationary, and the frequency which appears at the brushes is the frequency of the rotating field, regardless of the speed or direction of rotation of the armature.

This is the same as the operation of a d-c machine if an alternating voltage is applied to the shunt field. The voltage at the brushes would vary at the same frequency as the voltage applied to the field, independent of the rotation of the armature or the magnitude of the induced voltage. The magnitude of the electromotive force induced in the regulator armature is, however, proportional to the relative velocity of rotation of its synchronously revolving field and the rotor conductors. When the speed of the rotating field is N_s and the machine is rotating at a speed, N, in the same direction as the revolving field this voltage is $(N_s - N) \div N_s$ multiplied by the voltage induced in the armature at standstill. On the other hand, if the armature is rotating in the direction opposite to that of the revolving field, the voltage at the terminals is $(N_s + N)/N_s$ multiplied by the induced voltage at standstill.

In order to minimize the armature reactance of the regulating machine, a compensating winding is so placed on the stator that the magnetomotive force which it produces directly opposes that of the armature. The armature and the compensating winding carry the same current and if the effective number of turns of the two windings is the same, maximum compensation is accomplished. The only flux produced by the armature current is a leakage flux which may be interpreted as producing a reactance drop in the usual manner. It is this condition of compensation which will be considered henceforth. The magnetomotive force produced by the armature current is rotating at constant velocity, regardless of the armature speed. Likewise, the compensating winding produces a magnetomotive force which rotates in the same direction and at the same velocity as the armature magnetomotive force, but is directly opposed to it. For best compensation these two magnetomotive forces should be equal and opposite.

The compensating winding and armature are so connected that the voltages induced in them by the field flux are directly opposed. Since the two windings have the same effective number of turns, the voltages induced in them at standstill are equal and opposite. At any other speed the voltage induced in the compensating winding is the same, but that generated in the armature is changed as explained above. Let ϕ be the magnitude of the air-gap flux of the commutator machine and k be a constant involving number of turns, type of winding, and other quantities, and assume the armature to be rotating at speed N in the direction opposite to that of the rotating field. The voltage induced in the armature is then

$$\frac{N+N_s}{N_s} k\phi$$

That induced in the compensating winding is $k\phi$, and the voltage appearing at the terminals of the armature and compensating winding together is

$$E_a = \frac{N+N_s}{N_s} k\phi - k\phi = N\frac{k\phi}{N_s}$$

This shows that the electromotive force E_a appearing at the terminals of the armature and compensating winding together is directly proportional to the speed.

Since the machine is compensated, current flowing through the armature and compensating windings produces only leakage flux. Therefore the armature current induces no electromotive force in the field circuit. Then, with constant applied voltage and frequency the field current is the small, constant, exciting current, regardless of speed, load, or armature current of the machine.

The equivalent circuit of a single phase of the induction motor secondary and the regulator is illustrated in Figure 2. In this diagram and throughout this paper R_2 and X_2 represent the resistance and leakage reactance of one phase of the induction-motor secondary winding at standstill, R_a and X_a represent the corresponding quantities for the circuit comprising the armature and compensating winding of the regulating machine, and

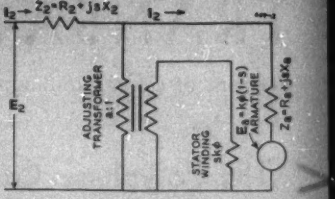


Figure 2. Equivalent circuit of a single phase of the drive

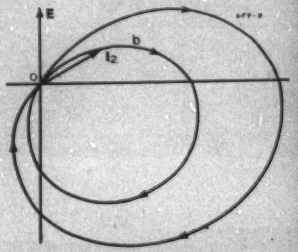
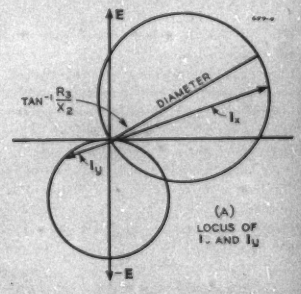


Figure 3. Locus of load component of secondary current of induction motor according to the exact theory



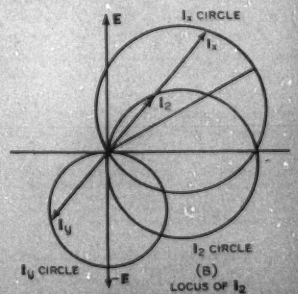


Figure 4. Loci of components of secondary current of induction motor

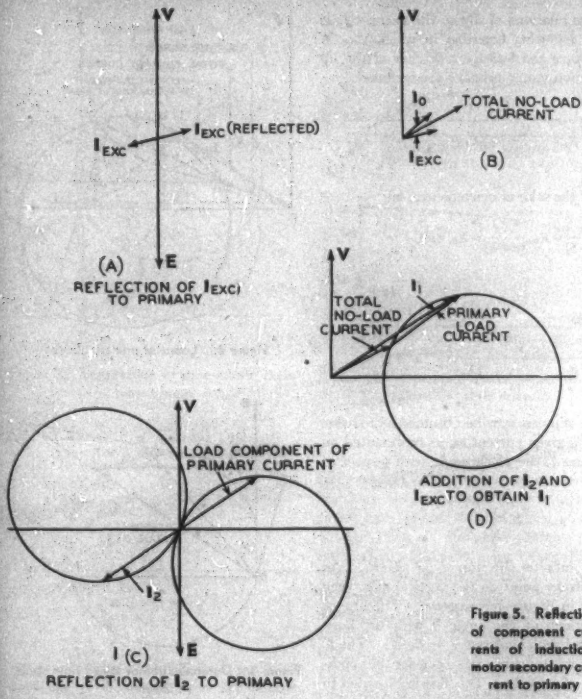


Figure 5. Reflection of component currents of induction-motor secondary current to primary

E_1 represents the voltage induced in one phase of the secondary of the induction motor. E_2 is the voltage induced in one phase of the regulator field winding and it is proportional to the value of flux in the air gap and the frequency of the applied voltage. This applied voltage is of slip frequency, since it is the slip-ring voltage of the induction motor. Therefore, $E_2 = k\phi s$, where s is the slip of the induction motor, ϕ is the air-gap flux of the polyphase commutator regulator, and k is a constant involving the number of turns, winding, and other factors, of the commutator regulator. The same flux generates the voltage in the armature, and if the armature is assumed to possess the same number of turns as the shunt field, the only difference between the expression for E_a, the armature circuit induced voltage, and E_2 is in the manner in which slip occurs. It has been mentioned previously that the voltage appearing at the armature terminals is directly proportional to the speed of the machine, and therefore, $E_a = k\phi(1 - s)$.

By neglecting the effect of exciting current of the commutator machine flowing through the induction-motor secondary, making $Z_2 = R_2 + jsX_2$, $Z_a = R_a + jsX_a$, and letting a be the turns ratio of the transformer in the field circuit, the following circuit equations are obtained:

$$E_1 - I_2(Z_2 + Z_a) = (1-s)k\phi \quad (1)$$

$$E_1 - I_2 Z_2 = ask\phi \quad (2)$$

If the voltage induced in one phase of the induction-motor rotor at standstill is E, then E_2 is equal to sE and:

$$I_2 = \frac{s^2(a+1)E - sE}{(a+1)sZ_1 - Z_2 + asZ_a} \quad (3)$$

If the load component of the secondary current of the induction motor is calculated according to equation 3 for different values of slip, the locus of the extremity of the current vector with respect to the voltage E is of the form indicated by the curve in Figure 3. The operating range as a motor is indicated by the segment ob of the inner loop, where o represents the no-load point and b the standstill point. Although theoretically correct, this locus possesses the disadvantage that all of the constants of both the induction motor and the commutator machine must be known in order to calculate it, and this computation must be carried out point by point as the locus is not a simple geometric figure.

If the voltage drop caused by the current flowing through the resistance of the secondary circuit of the induction motor is neglected when setting up the voltage equation for the stator circuit of the regulating machine, a circle locus defining the vector I_2 may be obtained which is a very good approximation of the theoretical curve in the operating range. When this assumption is made the voltage equations for the motor secondary take the following form:

$$E_2 - I_2(Z_2 + Z_a) = (1-s)k\phi \quad (4)$$

$$E_2 - jI_2 sX_2 = ask\phi \quad (5)$$

When sE is substituted for E_2 and the two equations are solved for I_2, the following result is obtained:

$$I_2 = \frac{(a+1)sE - E}{a(R_2+R_a) + jsa(X_2+X_a) + jsX_2 - jX_2} \quad (6)$$

For convenience, let $R_3 = a(R_2 + R_a)$ and $X_3 = a(X_2 + X_a) + X_2$. Then

$$I_2 = \frac{s(a+1)E - E}{R_3 + j(sX_3 - X_2)}$$

By making use of the principle of superposition, the following component currents are obtained:

$$I_2 = I_x + I_y \quad (7)$$

In which

$$I_x = \frac{s(a+1)E}{R_3 + j(sX_3 - X_2)}$$

and

$$I_y = \frac{-E}{R_3 + j(sX_3 - X_2)}$$

The currents I_x and I_y are always in time phase opposition. They may be considered as currents flowing in the impedance, $R_3 + j(sX_3 - X_2)$, caused by voltages $s(a + 1)E$ and $-E$ which are in time phase opposition. The locus of the extremity of the current vector I_y referred to the voltage E for varying slip is a circle as shown in Figure 4A. Its diameter is vertical and has a magnitude E/R_3. The locus of the extremity of the current vector I_x is also a circle as indicated in Figure 4A. Its diameter is

$$\frac{(a+1)E}{X_3} \cdot \frac{\sqrt{R_3^2 + X_3^2}}{R_3}$$

at an angle $\tan^{-1}(R_3/X_3)$ with the volt-

age vector E. The derivation of magnitude and position of these circles is given in Appendix I. The locus of the extremity of the vector I_4 obtained from equation 7 also is found to be a circle as illustrated in Figure 4B. The proof that it has a circle locus is presented in Appendix II.

All of this analysis has been carried out neglecting the exciting current of the polyphase commutator regulator and its associated transformer, which flows in the induction-motor secondary. This exciting current is directly proportional to the voltage applied to the field winding and inversely proportional to the frequency of this voltage. As the machines slow down due to increase in load, the slip increases and the frequency of the voltage applied to the regulator field increases proportionally. The voltage across the field winding increases also, though to a lesser degree because of the voltage drop I_2Z_2 in the secondary of the induction motor. Since the speed changes only slightly with load, the voltage and frequency applied to the field of the commutator machine are essentially unchanged. The changes which do occur produce tendencies in opposite directions. Therefore, for a given setting of the regulating transformer, the exciting current of the commutator machine remains substantially constant. It is assumed to remain entirely so in the analysis presented here.

The total secondary current of the induction motor is made up of the exciting current and the current I_2 just obtained. The magnitude and direction of the current in the primary winding of the induction motor resulting from these two secondary currents can be determined by reflecting them separately as vectors to the primary vector diagram. This procedure is indicated in Figure 5. The exciting current is reflected first and combined with the exciting current of the induction motor itself to give the total exciting current of the drive as shown in Figure 5B. The load component I_b of the secondary current when reflected to the primary winding produces a primary load component of current having a circle locus differing in magnitude from the secondary circle locus by the turns ratio of the motor as indicated in Figure 5C. Thus the primary current is the sum of the three components and is defined by a circle locus also. This is illustrated in Figures 5D and 6.

The characteristics of the drive may be predicted from the circle diagram of the input current.

The speed of the drive can be obtained from relations of slip to the current I_x in the following equation in which the resistance and leakage reactance of the induction motor primary are included.

$$I_x = \frac{V}{R_1 + \frac{R_2}{(a+1)s} + jX_1 + \frac{jX_2}{(a+1)} - \frac{jX_2}{(a+1)s}} \tag{8}$$

For the sake of convenience, let

$$\frac{R_2}{(a+1)} = R_b, \quad \frac{X_2}{(a+1)} = X_b, \text{ and}$$

$$X_1 + \frac{X_2}{(a+1)} = X_4$$

Then

$$I_x = \frac{V}{\frac{R_2}{s} + R_1 + jX_4 - \frac{jX_2}{s}} \tag{9}$$

The slip can now be obtained as follows. For a given current oe, as represented on Figure 7, the phase angle with respect to the voltage is

$$\tan^{-1}\theta = \frac{(sX_4 - X_b)}{(sR_1 + R_b)}$$

For infinite slip $\tan\theta = X_4/R_1$. An arbitrary point on the vertical axis, such as a in Figure 7 is selected. The line ab is drawn at the angle γ with the horizontal such that $\tan\gamma = R_1/X_4$. The I_x vector is tangent to its circle for the condition of zero slip. This line is extended to give the point d, and the standstill value of I_x is also extended until it intersects ab at f. The length db is then directly proportional to the slip. The line segment df is divided into 100 parts. Slip corresponding to any load current may be obtained by extending the corresponding I_x vector until it intersects this line and reading the slip directly. Proof of the validity of this procedure is found in Appendix III.

The power loss associated with the no-load current is assumed to remain constant for all values of load, just as is done in the treatment of the 2-element induction motor. This power loss is represented by the product of the in-phase component of the no-load current and the phase voltage.

Having determined the slip and the corresponding speed from the construction shown in Figure 7, the other characteristics may be determined by constructing the diagram for the motor shown in Figure 6. In this diagram (Figure 6) the load component of primary current is ob, and the copper loss for the current ob = (loss for oc)$(ob/oc)^2$, where oc is the load component of primary current for the blocked rotor condition. If the loss

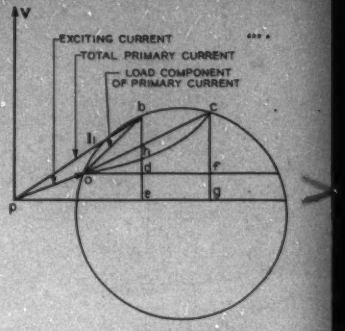


Figure 6. Locus of primary current

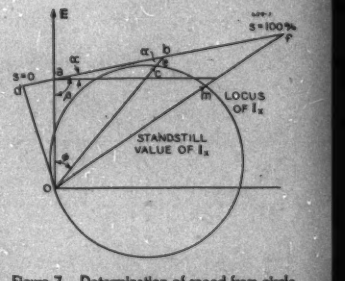


Figure 7. Determination of speed from circle diagram

for oc is known, the copper loss of the drive can be evaluated for all values of the load component of the current I_1, and the curve obc constructed such that the current dh when multiplied by the voltage, V, gives the copper loss caused by the current ob. Similarly other points on the curve can be obtained for different values of input current.

The different quantities for the drive now can be obtained corresponding to any value of current I_1.

1. Input = $(be)V$ watts per phase
2. Output = $(bh)V$ watts per phase
3. Iron loss, friction, and windage = $(de)V$ watts per phase
4. Copper loss = $(hd)V$ watts per phase
5. Efficiency = $\frac{(bh)}{(be)} \times 100$ per cent
6. Power factor = $\frac{(be)}{(pb)} \times 100$ per cent

All of these letters refer to Figure 6. The slip may be obtained from Figure 7.

7. Slip = $\left(\frac{db}{df}\right) \times 100$ per cent

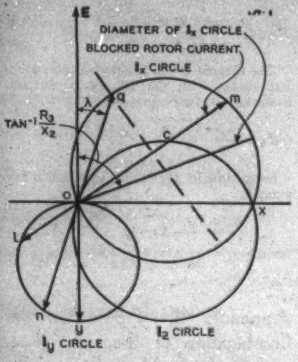


Figure 8. Construction of approximate circle current locus

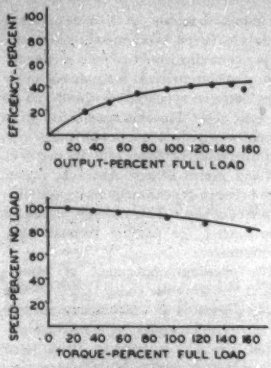
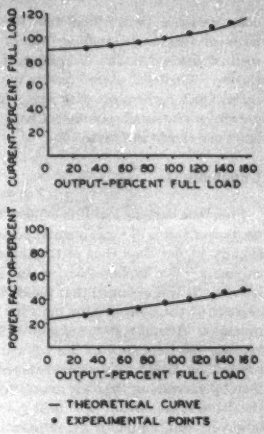


Figure 10. Operating characteristics of the adjustable-speed drive



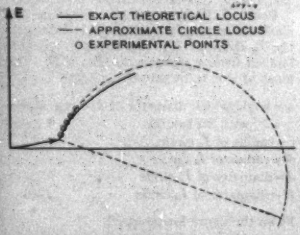


Figure 9. Input current loci of the drive according to both exact and approximate theories, and experimental points

8. Speed $= \left(1-\frac{db}{df_x}\right) \times$ synchronous speed

9. Torque = (horsepower output) $\times \frac{33{,}000}{2\pi N}$

On the basis of these expressions a complete set of characteristics can be predicted.

Experimental Results

In order to verify the theory thus far presented a complete set of tests was made upon a drive consisting of a 4-pole 5-horsepower wound-rotor induction motor and a polyphase commutator regulator of approximately 2-horsepower rating. The brushes of the regulator were so adjusted that the voltage appearing between them was directly opposed to the voltage applied to the primary of the adjustable transformer in its field circuit.

The method employed to obtain the locus of primary current involves a determination of (*a*) no-load voltage, current, and power input to the induction motor, (*b*) the blocked-rotor current, voltage, and input power taken both in the primary of the induction motor and in the armature circuit of the commutator machine, and (*c*) the determination of the voltage ratio *a*. Reduced voltages can be used to obtain data for determining blocked-rotor inputs at rated voltage. By making use of equation 7 for the standstill condition, and the experimentally determined value of *a*, the blocked-rotor current *om* of the I_x circle may be calculated from the blocked-rotor current *oc* of the primary current locus (see Figure 8). Likewise the blocked-rotor current *ol* of the I_y circle is determined.

The slip for which the component currents I_x and I_y are equal in magnitude can be obtained from equation 7. This value is found to be

$$s = \frac{1}{a+1}$$

Substituting this value of slip into the expression for I_x, it is then found that these two currents are equal when

$$I_x = \frac{E}{R_3 + j\left(\frac{X_3}{a+1} - X_3\right)}$$

Substituting the real value for X_3 (see list of symbols), it is found that this current has a power factor angle λ with respect to the stator voltage E such that

$$\tan\lambda = \frac{aX_3}{(a+1)R_3}$$

Since the diameter of I_y circle is determined in direction and the point *l* is now known, the I_y circle can be constructed. The diameter of this circle is E/R_3 in length. The resistance R_3 is equal to E divided by the current *oy*. The value of X_3 is obtained from the blocked-rotor readings taken on the regulator. These values can be used to determine the angle λ. This angle and the I_y circle determine the direction and magnitude of the current *on* which was specified as being equal to and opposite to a current vector *oq* having its extremity on the I_x circle. The points *o*, *q*, and *m* determine the I_x circle. The intersection of the I_x circle with the horizontal axis at *x* is a point on the I_3 circle. The points *o*, *c*, and *x* determine the location of the I_3 circle.

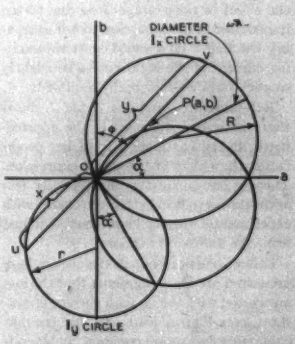


Figure 11. Proof that the terminus of the I_x vector has a circle locus

The theoretically accurate locus, the approximate circle, and the experimental points are shown in Figure 9. Complete

characteristics were predicted on the basis of this circle, making use of the method devised in the discussion of the theory. These calculated results were in quite good agreement with the experimentally measured points. Characteristics are shown in Figure 10.

Conclusions

From the current loci it is evident that the power factor of experimental points is slightly higher than that of the theoretical locus. The explanation for this is as follows. It was assumed that the exciting current of the commutator machine was constant. Actually, it decreases with load because the frequency of the voltage impressed on the regulator field increases, thereby increasing the field reactance as the drive slows down. The field voltage, however, was found to be substantially constant with change in speed because of the effect of the voltage drop due to the impedance in the induction-motor secondary winding. This would cause the exciting current of the regulator to be slightly smaller than was originally assumed.

Reference to equations 3 and 7 shows that the impedance used in the approximate theory has a slightly higher power factor than that of the exact expression. This explains why the theoretically less accurate curve is in better agreement with experimental results than that obtained from the more exact theory.

Other errors present in the theory here presented are the statements that the loss associated with the no-load current is constant, regardless of load, and that the machine impedances are constant, independent of current. Both of these errors are inherent in normal induction motor theory.

The polyphase commutator regulator was of considerably lower power rating than the induction motor and hence possessed a higher armature resistance than was desirable. In order to load the induction motor fully, it was necessary to send currents through the armature of this machine considerably in excess of its normal current capacity. This resulted in abnormally high copper loss and the correspondingly low efficiencies observed.

It will be observed that the voltage impressed on the commutator machine is only a fraction of the voltage rating of the induction motor secondary, this fraction being the per cent slip at full load. The current capacity of the regulator, however, should be equal to that of the induction motor secondary winding, and therefore its kilovolt-ampere rating is the product of full-load slip and the rating of the induction motor. A drive designed to operate between synchronous speed and 50 per cent slip would require a commutator machine twice as large as one operating between synchronous speed and 25 per cent slip. For this reason the drive normally employed is a double-range system operating between plus 25 per cent slip and minus 25 per cent slip, rather than between synchronous speed and plus 50 per cent slip. This requires an ohmic drop exciter for passing through synchronism.

The excellent agreement of experimental results with those based on the theory presented in this paper indicates the theory to be sound. The method presented here may be used to obtain from no-load tests or design data the operating characteristics of the drive employing the polyphase commutator regulator. Results have shown the accuracy achieved to be high.

Appendix I. Derivation of Position and Magnitude of the Circle Locus of I_z for the Compensated Commutator Machine

$$I_z = \frac{s(a+1)E}{R_2 + j(sX_2 - X_3)} = \frac{s(a+1)E}{\sqrt{R_2^2 + (sX_2 - X_3)^2}}$$

This is readily recognized as the equation of a circle when it is written

$$I_z = \frac{(a+1)E}{\frac{R_2}{s} + j\left(X_2 - \frac{X_3}{s}\right)}$$

The diameter of the circle is the maximum value which I_z attains. In order to obtain the value of slip for which I_z is a maximum, this expression is differentiated with respect to s and equated to zero.

$$\frac{dI_z}{ds} = \frac{\left[\sqrt{R_2^2 + (sX_2 - X_3)^2}(a+1)E - s(a+1)E \times E[R_2^2 + (sX_2 - X_3)^2]^{-1/2}(sX_2 - X_3)X_2\right]}{R_2^2 + (sX_2 - X_3)^2}$$

Multiplying through by

$$[R_2^2 + (sX_2 - X_3)^2]^{1/2}$$

and clearing fractions gives

$$R_2^2 + (sX_2 - X_3)^2 - sX_2(sX_2 - X_3) = 0$$

Simplifying and solving for s yields

$$s = \frac{R_2^2 + X_3^2}{X_2 X_3}$$

Substitute this in the expression for I_z.

$$\text{Max } I_z = \frac{R_2^2 + X_3^2}{X_2 X_3} \cdot \frac{(a+1)E}{\sqrt{R_2^2 + \left(\frac{R_2^2 + X_3^2}{X_3} - X_3\right)^2}}$$

Multiply through by X_3 and simplify.

$$\text{Max } I_z = \frac{(a+1)E}{X_3}\frac{\sqrt{R_2^2 + X_3^2}}{R_2}$$

The tangent of the angle which the diameter makes with the voltage is obtained from the following expression:

$$\tan \psi = \frac{sX_2 - X_3}{R_2}$$

Substitute in the value of s for maximum I_z.

$$\tan \psi = \frac{\frac{R_2^2 + X_3^2}{X_3} - X_3}{R_2} = \frac{R_2}{X_3}$$

Appendix II. Proof That the Combination of the I_z and I_y Circles Is Also a Circle

Employ a as the horizontal co-ordinate and b as the vertical co-ordinate in Figure 11.

Point P is obtained by extending the chord ov of the I_z circle until it intersects the I_y circle at u. The distance $uo = x$ is laid off from v along ov to obtain P. The locus of P is to be proved a circle.

α = angle which diameter of I_z circle makes with horizontal
r = radius of I_y circle
R = radius of I_z circle
d = diameter of I_y circle
D = diameter of I_z circle

From the figure for point P:

$a = (y - x)\sin\theta$
$b = (y - x)\cos\theta$
$x = d\cos\theta$
$y = D(\sin\theta\cos\alpha + \cos\theta\sin\alpha)$
$y - x = D\sin\theta\cos\alpha + \cos\theta(D\sin\alpha - d)$

Substitute in the expression for a and b the value of $y - x$. This yields:

$$a = D\sin^2\theta\cos\alpha + \sin\theta\cos\theta(D\sin\alpha - d) \quad (10)$$

$$b = D\sin\theta\cos\theta\cos\alpha + \cos^2\theta(D\sin\alpha - d) \quad (11)$$

Let:

$D\sin\alpha - d = m$

From equation 10

$$\sin\theta\cos\theta = \frac{a - D\sin^2\theta\cos\alpha}{m}$$

Substitute this into equation 11.

$$b = \frac{Da}{m}\cos\alpha - \frac{D^2}{m}\cos^2\alpha\sin^2\theta + m\cos^2\theta$$

Now

$$\cos^2\theta = 1 - \sin^2\theta$$

$$b = \frac{Da}{m}\cos\alpha - \left(\frac{D^2\cos^2\alpha + m^2}{m}\right)\sin^2\theta + m$$

$$\sin^2\theta = \frac{\frac{Da\cos\alpha}{m} + m - b}{\frac{D^2\cos^2\alpha}{m} + m} = z^2 \quad (12)$$

letting $n=\sin\theta$. Rewriting equation 10 gives

$$a=D\sin^2\theta\cos\alpha+m\sin\theta\sqrt{1-\sin^2\theta}$$

Substitute $n=\sin\theta$.

$$a=Dn^2\cos\alpha+nm\sqrt{1-n^2}$$

$$\sqrt{1-n^2}=\frac{a-Dn^2\cos\alpha}{mn}=\frac{a}{mn}-\frac{Dn}{m}\cos\alpha$$

Eliminate the square root.

$$0=-m^2(1-n^2)+\frac{a^2}{n^2}+D^2n^2\times\cos^2\alpha-2aD\cos\alpha$$

Substitute for n^2 from equation 12.

$$\frac{\frac{Da\cos\alpha}{m}+m-b}{\frac{D^2\cos^2\alpha}{m}+m}$$

Then

$$-m^2\frac{\frac{D^2\cos^2\alpha}{m}-\frac{Da\cos\alpha}{m}+b}{\frac{D^2\cos^2\alpha}{m}+m}+a^2\frac{\frac{D^2\cos^2\alpha}{m}+m}{\frac{Da\cos\alpha}{m}+m-b}+\frac{D^2\cos^2\alpha\left(\frac{Da\cos\alpha}{m}+m-b\right)}{\frac{D^2\cos^2\alpha}{m}+m}-2aD\cos\alpha=0$$

And

$$\frac{\left[\begin{matrix}-D^2m^2\cos^2\alpha+aD^2m^2\cos\alpha-bm^2+\\aD^2\cos^2\alpha+D^2m^2\cos^2\alpha-bD^2m\cos^2\alpha\end{matrix}\right]}{D^2\cos^2\alpha+m^2}+\frac{a^2D^2\cos^2\alpha+a^2m^2}{aD\cos\alpha+m^2-bm}-2aD\cos\alpha=0$$

Clear fractions:

$$\begin{aligned}&a^2D^2m^2\cos^2\alpha-abD^2m^2\cos\alpha+a^2D^4\times\\&\cos^4\alpha-abD^2m\cos^3\alpha+aD^2m^4\times\\&\cos\alpha-bm^4+aD^2m^2\cos^2\alpha-bD^2m^2\times\\&\cos^2\alpha-abDm^2\cos\alpha+b^2m^2-abD^2m\times\\&\cos^2\alpha+b^2D^2m^2\cos^2\alpha+a^2D^4\times\\&\cos^4\alpha+a^2D^2m^2\cos^2\alpha+a^2D^2m^2\times\\&\cos^2\alpha+a^2m^4-2a^2D^2\cos^4\alpha-2aD^2m^2\times\\&\cos^2\alpha+2abD^2m\cos^2\alpha-2a^2D^2m^2\times\\&\cos^2\alpha-2aDm^2\cos\alpha+2abDm^2\times\\&\cos\alpha=0\end{aligned}$$

$$a^2(D^2m^2\cos^2\alpha+m^4)-a(D^2m^2\cos^2\alpha+Dm^4\times\cos\alpha)+b^2(D^2m^2\cos^2\alpha+m^4)-b\times(D^2m^2\cos^2\alpha+m^4)=0$$

$$a^2-a\left[\frac{D\cos\alpha(D^2\cos^2\alpha+m^2)}{D^2\cos^2\alpha+m^2}\right]+b^2-b\left[m\frac{D^2\cos^2\alpha+m^2}{D^2\cos^2\alpha+m^2}\right]=0$$

$$\left(a^2-aD\cos\alpha+\frac{D^2}{4}\cos^2\alpha\right)+\left(b^2-bm+\frac{m^2}{4}\right)=\frac{D^2}{4}\cos^2\alpha+\frac{m^2}{4}$$

This is

$$\left(a-\frac{D}{2}\cos\alpha\right)^2+\left(b-\frac{m}{2}\right)^2=\frac{D^2\cos^2\alpha+m^2}{4}$$

This is the equation of a circle with center at $D\cos\alpha/2$, $m/2$.

Appendix III. Proof That the Line *db* of Figure 7 Is Proportional to Slip

The line ab of Figure 7 is drawn at an angle γ with the horizontal such that $\tan\gamma=R_1/X_s$. Point b is the intersection of the I_z vector with the line making the angle γ with the horizontal. Using the notation of Figure 7, the following equality may be written:

By the law of sines

$$\frac{ab}{\sin\theta}=\frac{ao}{\sin\alpha_1}$$

$\alpha_1=\angle abo$

$\beta=\angle oab$

$\alpha_1=180^\circ-(\beta+\theta)$

$\sin[180^\circ-(\beta+\theta)]=\sin(\beta+\theta)$

$$ab=\frac{ao\sin\theta}{\sin(\beta+\theta)}=\frac{ao\sin\theta}{\sin\theta\cos\beta+\cos\theta\sin\beta}$$

Divide through by $\cos\theta$

$$ab=ao\tan\theta\frac{1}{\tan\theta\cos\beta+\sin\beta}$$

Now

$\cos\beta=-\sin\gamma$, $\sin\beta=\cos\gamma$

$$ab=ao\tan\theta\frac{1}{-\tan\theta\sin\gamma+\cos\gamma}$$

The functions of theta and gamma are

$$\tan\theta=\frac{X_s-\frac{X_\theta}{s}}{R_1+\frac{R_\theta}{s}}\qquad\sin\gamma=\frac{R_1}{\sqrt{R_1^2+X_s^2}}$$

$$\tan\gamma=\frac{R_1}{X_s}\qquad\cos\gamma=\frac{X_s}{\sqrt{R_1^2+X_s^2}}$$

When these values are substituted in the expression for ab, the following result is obtained:

$$ab=ao\frac{X_s-\frac{X_\theta}{s}}{R_1+\frac{R_\theta}{s}}\times\frac{1}{\frac{X_s-\frac{X_\theta}{s}}{R_1+\frac{R_\theta}{s}}\cdot\frac{(-R_1)}{\sqrt{R_1^2+X_s^2}}+\frac{X_s}{\sqrt{R_1^2+X_s^2}}}$$

Clearing fractions yields

$$ab=ao(sX_s-X_\theta)\frac{\sqrt{R_1^2+X_s^2}}{R_1X_\theta+X_sR_\theta}$$

At zero slip ob of Figure 7 is tangent to the I_z circle. Under these conditions ab is equal to ad. The magnitude of ab for zero slip is

$$ab=ad=aoX_\theta\frac{\sqrt{R_1^2+X_s^2}}{R_1X_\theta+X_sR_\theta}$$

Now

$$db=ab+da=ao(sX_s-X_\theta+X_\theta)\frac{\sqrt{R_1^2+X_s^2}}{R_1X_\theta+X_sR_\theta}$$

$$db=ao(sX_s)\frac{\sqrt{R_1^2+X_s^2}}{R_1X_\theta+X_sR_\theta}$$

The length db, then, is directly proportional to the slip.

Appendix IV. List of Symbols

a = ratio of number of turns in primary to number of turns in secondary of adjusting transformer in field circuit of polyphase commutator regulator

E = the voltage induced in one phase of the induction motor secondary by the mutual flux at standstill

E_1 = the voltage induced in one phase of the armature winding of the compensated commutator regulator by the mutual flux

E_2 = the voltage induced in one phase of the induction motor secondary by the mutual flux. It is sE where s is the slip

E_a = the effective generated voltage per phase appearing at the terminals of the armature and compensating winding together for the compensated commutator machine. It is $E_1-E_2=k\phi(1-s)$

E_c = the voltage induced in one phase of the compensating winding of the commutator machine by the mutual flux

E_s = the voltage induced in one phase of the stator winding of the commutator machine by the mutual flux. $E_s=k\phi s$

I_1 = total primary current of induction motor

I_2 = total load component of secondary current of induction motor

I_a = armature current of polyphase commutator regulator

I_{exc} = exciting current of polyphase commutator regulator

I_o = no-load current of induction motor alone

I_x = component of I_2 due to $s(a+1)E$ for the compensated drive

I_y = component of I_2 due to $-E$ for the compensated drive

N = speed of drive in revolutions per minute

N_0 = no-load speed of drive in revolutions per minute

N_s = synchronous speed of drive in revolutions per minute

Formulas for the Inductance of Coaxial Busses Comprised of Square Tubular Conductors

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BY virtue of its axial symmetric geometry, the coaxial tubular bus possesses certain very desirable electrical and mechanical characteristics. Low inductance contributes to good voltage regulation. Reduced skin and proximity effects minimize line losses and average temperature rise under load. Axial-symmetric distribution of skin and proximity effects reduces current density distortion and attendant hot-spot concentrations, hence enables a greater current rating for a specified maximum copper temperature. As electromagnetic forces between conductors are eliminated largely, mechanical bracing against short-circuit forces correspondingly can be reduced. The nested conductors require less space for installation and a smaller supporting structure than they would if arranged side by side.

Yet, despite these desirable characteristics, the paucity of published descriptions of actual installations[1,2,3] indicates that few coaxial busses have been constructed to date. However, until recently factory distribution loads at frequencies greater than 60 cycles were uncommon. Again, most heavy 60-cycle loads were supplied over relatively short distances. As these conditions are such that satisfactory 60-cycle operation can be obtained with the more conventional, though less electrically effective, construction of conductors placed side by side, this limited use of coaxial busses is not surprising. Now, however, by virtue of manufacturing procedures and techniques developed during the war, the bus designer is faced with the necessity of designing heavy distribution busses which are not only long but also are to operate at froquencies of several hundred cycles and higher. But, the electrical characteristics of the coaxial bus are such that it is especially suited to satisfactory operation under either or both of these conditions. Hence it is to be expected that in the near future coaxial busses will find greater use than they have hitherto.

At present, coaxial busses are constructed of circular tubular conductor, of square tubular conductor, and of structural tubular conductor comprised of two slightly separated channels or angles placed flange to flange. To predetermine the operating characteristics of these busses requires knowledge of the a-c resistance, the a-c inductance, the copper temperature under load, and the mechanical forces exerted during short-circuit. Formulas[4] for calculating all four of these quantities are available for busses comprised of a circular tubular conductor. But for a square or structural tubular conductor, though formulas are available for calculating the a-c resistance,[5,6] the copper temperature,[6] and the short-circuit forces,[4] formulas for calculating the a-c inductance, often the determining factor in the design of the bus, are not available.

Such formulas are derived in this paper, it being assumed that the conductors are nonmagnetic, of such lengths that end effects are negligible, of uniform thickness, right-cornered, and carry currents distributed uniformly over their cross sections. Of these five conditions, the first three are satisfied in practice. The fourth, however, though essential to tractable analysis, is usually not true in practice. Square tubes, channels, and angles, drawn, rolled, bent, or otherwise formed in one piece, have rounded edges, but the error introduced by neglecting the rounded edges is small. Commonly, the result obtained, though a bit low, is yet sufficiently accurate for the work in hand. In any case, the incremental inductance associated with the rounded edges can be approximated closely by a simple semi-empirical formula derived by Dwight and Wang.[7] Finally, though skin and proximity effects render the current density over the cross sections of the conductors slightly nonuniform, the analysis in "Corrections for Rounded Edges and for Skin and Proximity Effects," later in this paper, indicates that at power frequencies the a-c inductance is practically identical with the d-c inductance.

Inasmuch as these five postulates are granted as consistent with practice, derivations of the desired formulas, though lengthy, are not difficult. The

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R_1 = primary resistance per phase of induction motor

R_2 = secondary resistance per phase of induction motor

$R_s = a(R_2 + R_a)$

$R_a = \dfrac{R_2}{(a+1)}$

s = slip measured from zero at synchronous speed

X_1 = primary leakage reactance per phase of induction motor at standstill

X_2 = secondary leakage reactance per phase of induction motor at standstill

$X_3 = a(X_2 + X_a) + X_3$

$X_4 = \dfrac{X_3}{(a+1)} + X_1$

X_a = leakage reactance per phase of armature of polyphase commutator regulator with drive at standstill

$X_s = \dfrac{X_3}{(a+1)}$

V = applied voltage per phase of induction motor

Z_2 = impedance per phase of induction motor secondary

Z_a = impedance per phase of armature of polyphase commutator regulator

α = angle which line tangent to I_s circle at origin makes with voltage vector

$\beta = \tan^{-1}\dfrac{X_4}{R_1}$

$\gamma = \tan^{-1}\dfrac{R_1}{X_4}$

ϕ = total air-gap flux of polyphase commutator regulator

ψ = angle which the diameter of the I_s circle makes with the voltage vector = $\tan^{-1}\dfrac{R_3}{X_3}$

$\lambda = \tan^{-1}\dfrac{aX_a}{(a+1)R_3}$

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conductor cross sections can be considered in various fashions as combinations of parallel-sided square areas. By virtue of geometric mean distance theory, the inductance can be expressed in terms of the self and mutual geometric mean distances of these square areas. These geometric mean distances can be calculated from known formulas. Accordingly, determination of the inductance as a function of the parameters defining the geometry of the bus reduces, essentially, to specific determination of the geometric mean distances involved and substitution of them in the general equation for the inductance.

The general formula comprises 36 terms. A simple approximate formula similarly derived, but on the assumption that the conductors can be considered as being indefinitely thin and hence having cross sections comprised of line segments, affords values sufficiently accurate for many design purposes. As a further convenience to numerical computation, this formula is epitomized in a single curve. Conductors which are indefinitely thin are limiting cases of conductors of finite thickness, a physical consideration which indicates that the approximate formula can be considered as a limiting case of the general formula. Analytical confirmation of this deduction provides a simultaneous check of the correctness of the general and approximate formulas.

The desired formulas, having been obtained and checked, are used as illustrated by calculation of the inductance of typical busses constructed of square tubular conductors. Changes in inductance resulting from rounded corners on the conductors and from skin and proximity effects are discussed in detail. Procedures for calculating the inductance of coaxial busses, constructed of channels or angles, are advanced. Illustratively, the inductance of a bus constructed of channels is calculated and found to be in good agreement with the experimentally determined value. Finally, procedure for calculating the inductance of polyphase coaxial busses, comprised of square tubular conductors, is outlined.

General Relationships

From well-known theory,[8,9] the inductance of a bus comprised of two long parallel cylindrical nonmagnetic conductors, each of an arbitrary cross section, is

$$L = 2 \log D_{ab}^{2} / D_{aa} D_{bb} \text{ abhenrys per centimeter of bus length} \quad (1)$$

where D_{aa} and D_{bb} are the self geometric mean distances, and D_{ab} is the mutual geometric mean distance of the conductor cross sections.

If each of the two conductors is constructed of several subconductors connected in parallel, m composing the conductor of a cross section S_a and n that of a cross section S_b, equation 1 can be written

$$L = -(2/I^2) \sum_{i=1}^{m+n} \sum_{j=1}^{m+n} w_i w_j S_i S_j \log D_{ij} \quad (2)$$

where I is the bus current; w_i the current density in the ith subconductor of the sectional area S_i, taken positive for current flow in one direction and negative for current flow in the opposite direction; and $D_{ij} \equiv D_{ji}$ is the geometric mean distance between areas S_i and S_j.

If $S_i = RS$ and $S_j = R'S'$ are two arbitrarily located parallel-sided rectangular areas (Figure 1), the mutual geometric mean distance is

$$S_i S_j \log D_{ij} = -(25/12) S_i S_j - (1/24) \times \sum_{p=1}^{4} \sum_{q=1}^{4} (-1)^{p+q} K(A_p, B_q) \quad (3)$$

where

$$K(A_p, B_q) = (A_p^4 - 6A_p^2 B_q^2 + B_q^4) \times \log (A_p^2 + B_q^2)^{1/2} - 4A_p B_q^3 \times \tan^{-1}(A_p/B_q) - 4A_p^3 B_q \tan^{-1}(B_q/A_p) \quad (4)$$

and

$$A_1 = |D+R+R'|, \; A_2 = |D+R|, \; A_3 = |D|, \; A_4 = |D+R'| \quad (5)$$

$$B_1 = |P+S+S'|, \; B_2 = |P+S|, \; B_3 = |P|, \; B_4 = |P+S'| \quad (6)$$

Derivation of the General Formula

Consider a bus comprised of two coaxial square tubular conductors (Figure 2). Each of the conductors can be considered as constructed of two subconductors: one of a full square cross section wherein current exists in the same direction as in the tubular conductor, the other of a smaller full square cross section having current in the opposite direction. Hence $m = n = 4$, and from equation 2

$$L = -(2/I^2) \sum_{i=1}^{4} \sum_{j=1}^{4} w_i w_j S_i S_j \log D_{ij} \quad (7)$$

By definition, $D_{ij} \equiv D_{ji}$. By inspection of Figure 2, $w_1 = -w_2 = I/(a^2 - b^2)$ and $w_3 = -w_4 = -I/(c^2 - d^2)$. Utilizing these relationships in equation 7 yields

$$L = [-2/(a^2-b^2)^2][S_1^2 \log D_{11} + S_2^2 \log D_{22} - 2S_1 S_2 \log D_{12}] + [-2/(c^2-d^2)^2] \times [S_3^2 \log D_{33} + S_4^2 \log D_{44} - 2S_3 S_4 \times \log D_{34}] + [4/(a^2-b^2)(c^2-d^2)] \times [S_1 S_3 \log D_{13} - S_1 S_4 \log D_{14} - S_2 S_3 \times \log D_{23} + S_2 S_4 \log D_{24}] \quad (8)$$

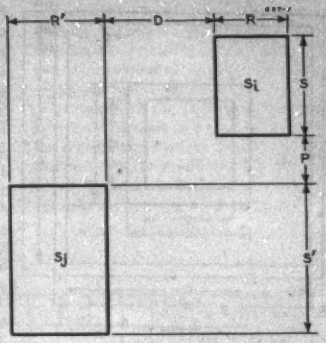


Figure 1

Determining the ten geometric mean distances in the right-hand member of equation 8 by use of equations 3 to 6, substituting appropriately in equation 8, and collecting terms (a detailed analysis appears in Appendix I) yields

$$\begin{aligned} L = {} & \{[-1/6(a^2-b^2)^2][12a^4 \log a + 12b^4 \times \log b - (a-b)^4 \log (a-b) - (a+b)^4 \times \log (a+b) + (a^4 - 6a^2b^2 + b^4) \times \log (a^2+b^2) + 10(a^4+b^4) \log 2 + 8ab \times (a^2-b^2) \tan^{-1}(a-b)/(a+b) + \pi \times (a^2-b^2)(a-b)^2]\} + [[-1/6(c^2-d^2)^2] \times [12c^4 \log c + 12d^4 \log d - (c-d)^4 \times \log (c-d) - (c+d)^4 \log (c+d) + (c^4 - 6c^2d^2 + d^4) \log (c^2+d^2) + 10(c^4+d^4) \log 2 + 8cd(c^2-d^2) \times \tan^{-1}(c-d)/(c+d) + \pi(c^2-d^2) \times (c-d)^2]\} + [[-1/6(a^2-b^2) \times (c^2-d^2)][(a-d)^4 \log (a-d) + (a+d)^4 \log (a+d) - (a^4 - 6a^2d^2 + d^4) \times \log (a^2+d^2) - (b-d)^4 \log (b-d) - (b+d)^4 \log (b+d) + (b^4 - 6b^2d^2 + d^4) \times \log (b^2+d^2) - (a-c)^4 \log (a-c) - (a+c)^4 \log (a+c) + (a^4 - 6a^2c^2 + c^4) \times \log (a^2+c^2) + (b-c)^4 \log (b-c) + (b+c)^4 \log (b+c) - (b^4 - 6b^2c^2 + c^4) \times \log (b^2+c^2) - 8ad(a^2-d^2) \times \tan^{-1}(a-d)/(a+d) + 8bd(b^2-d^2) \times \tan^{-1}(b-d)/(b+d) + 8ac(a^2-c^2) \times \tan^{-1}(a-c)/(a+c) - 8bc(b^2-c^2) \times \tan^{-1}(b-c)/(b+c) - \pi(a^2-d^2) \times (a-d)^2 + \pi(b^2-d^2)(b-d)^2 + \pi(a^2-c^2)(a-c)^2 - \pi(b^2-c^2)(b-c)^2]\} \end{aligned} \quad (9)$$

This is the desired formula for the inductance of a single phase bus. Further, it enables calculation of the inductance of a polyphase bus as outlined in "Polyphase Coaxial Busses."

Corroboration of Equation 9

In yet another fashion, each square tubular conductor can be assumed as constructed of four subconductors, each of a rectangular cross section and having

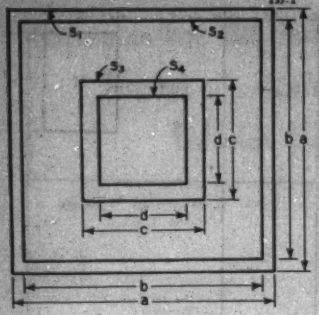


Figure 2

current in the same direction as in the tubular conductor (Figure 3). Hence $m=n=8$, and from equation 2

$$L=-(2/I^2)\sum_{i=1}^{8}\sum_{j=1}^{8}w_iw_jS_iS_j\log D_{ij} \qquad (10)$$

By definition, $D_{ij}=D_{ji}$. By virtue of the geometric symmetries apparent in Figure 3, $D_{11}=D_{33}$, $D_{22}=D_{44}$, $D_{55}=D_{77}$, $D_{66}=D_{88}$, $D_{12}=D_{14}=D_{23}=D_{34}$, $D_{56}=D_{58}=D_{67}=D_{78}$, $D_{15}=D_{37}$, $D_{26}=D_{48}$, $D_{17}=D_{35}$, $D_{28}=D_{46}$, $D_{16}=D_{18}=D_{36}=D_{38}$, and $D_{25}=D_{27}=D_{45}=D_{47}$. Further, $S_1=S_3$, $S_2=S_4$, $S_5=S_7$, $S_6=S_8$; $w_1=w_2=w_3=w_4=I/-(a^2-b^2)$, and $w_5=w_6=w_7=w_8=-I/-(c^2-d^2)$. Utilizing these relationships in equation 10 yields

$$\begin{aligned}L=4\{&[-1/(a^2-b^2)^2][S_1^2(\log D_{11}+\log D_{13})+S_2^2(\log D_{22}+\log D_{24})+4S_1S_2\log D_{12}]+[-1/(c^2-d^2)^2]\times[S_5^2(\log D_{55}+\log D_{57})+S_6^2(\log D_{66}+\log D_{68})+4S_5S_6\log D_{56}]+[2/(a^2-b^2)\times(c^2-d^2)]\{S_1S_5(\log D_{15}+\log D_{17})+S_2S_6(\log D_{26}+\log D_{28})+2S_1S_6\times\log D_{16}+2S_2S_5\log D_{25}\}\} \qquad (11)\end{aligned}$$

Determining the 16 geometric mean distances in the right-hand member of equation 11 as detailed in Appendix II, substituting appropriately in equation 11, and collecting terms yields, corroboratively, equation 9.

Obviously, this corroboration can be interpreted as a check of the correctness of the expressions, derived in Appendixes I and II, for the geometric mean distances indicated in equations 8 and 11.

Approximations to General Formula

The general formula for the inductance comprises 36 terms: 22 logarithmic, 6 arctangentic, and 8 algebraic. But by use of the proper tools (an electric calculating machine and the 15-place Work Projects Administration tables[10] of natural logarithms and arctangents), the computation incident to the calculation of the inductance of a given bus can be effected without difficulty. The computation, however, will be fairly lengthy. For this reason it is most desirable to have approximate formulas which enable rapid determination of values accurate enough for much (in some instances, all) of the computation incident to the final design of a bus.

A means of deriving such formulas stems from an earlier investigation[11] of the inductance of a coplanar bus comprised of rectangular tubular conductors. Therein, values of inductance calculated from the general formula were found to be in excellent agreement with values of inductance calculated from much simpler formulas derived by Dwight and Wang,[7] on the basis that the conductors are indefinitely thin. That is, they have cross sections comprised of line segments.

Consider, then, the cross section of each conductor as constructed of four line segments (Figure 4). Hence $m=n=8$, and from equation 8

$$L=-(2/I^2)\sum_{i=1}^{8}\sum_{j=1}^{8}w_iw_jS_iS_j\log D_{ij} \qquad (12)$$

By definition, $D_{ij}=D_{ji}$. By virtue of the geometric symmetries apparent in Figure 4, $D_{11}=D_{22}=D_{33}=D_{44}$, $D_{55}=D_{66}=D_{77}=D_{88}$, $D_{12}=D_{14}=D_{23}=D_{34}$, $D_{56}=D_{58}=D_{67}=D_{78}$, $D_{13}=D_{24}$, $D_{57}=D_{68}$, $D_{15}=D_{26}=D_{37}=D_{48}$, $D_{17}=D_{35}=D_{28}=D_{46}$, and $D_{16}=D_{18}=D_{25}=D_{27}=D_{36}=D_{38}=D_{45}=D_{47}$. Further, $S_1=S_3$, $S_2=S_4$, $S_5=S_7$, $S_6=S_8$; $w_1=w_2=w_3=w_4=I/4a$, and $w_5=w_6=w_7=w_8=-I/4c$. Utilizing these relationships in equation 12 yields

$$\begin{aligned}L=(-1/2)&\{\log D_{11}+2\log D_{12}+\log D_{13}\}+(-1/2)\{\log D_{55}+2\log D_{56}+\log D_{57}\}+[\log D_{15}+2\log D_{16}+\log D_{17}] \qquad (13)\end{aligned}$$

Determining the nine geometric mean distances in the right-hand member of equation 13 as detailed in Appendix III, substituting appropriately in equation 13, and collecting terms yields

$$\begin{aligned}L=&[(a+c)^2/2ac]\log(a+c)-[(a-c)^2/2ac]\times\log(a-c)-\log\{(ac)^2/(a^2+c^2)\}-[(a^2-c^2)/ac]\tan^{-1}[(a-c)/(a+c)]+\pi(a^2-c^2)/4ac-3\log 2 \qquad (14)\end{aligned}$$

Simple algebraic manipulation of the logarithmic terms of equation 14 yields alternative formulas especially convenient to numerical computation. Thus

$$\begin{aligned}L=\log&[(r^{-1}+r)(r^{-1}-r)]-1/2(r^{-1}+r)\times\log[(1-r)/(1+r)]+(r^{-1}-r)\times[\pi/4-\tan^{-1}(1-r)/(1+r)]-3\log 2 \qquad (15)\end{aligned}$$

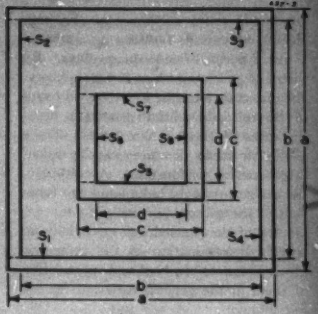


Figure 3

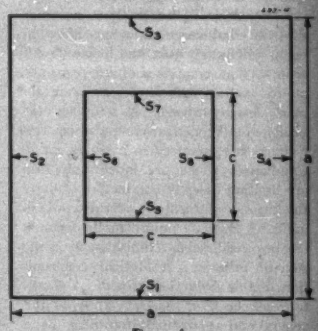


Figure 4

where $r=c/a$. Again

$$\begin{aligned}L=\log&(1+A^2)-2\log(1-A^2)-(1/2r)\times(1-r)^2\log A+(r^{-1}-r)\times(\pi/4-\tan^{-1}A) \qquad (16)\end{aligned}$$

where $A=(1-r)/(1+r)$.

For purposes of computation, these approximate formulas possess considerable advantage over the general formula. The latter comprises 36 terms, the former only a few terms. Moreover, the coefficients and arguments of these few terms are quite simple. Therefore, by virtue of the fewness and simplicity of the terms comprising the approximate formulas, they afford rapid computation. In fact, slide rule calculation is quite feasible; commonly, a 20-inch rule will afford values correct to a number of digits sufficient for most design work. But even slide rule calculation can be dispensed with in much work. The curves of Figure 5, plotted from equation 16, afford sufficiently accurate values. For actual use, of course, Figure 5 is too small, but the designer can plot his own curves from the co-ordinates tabulated in Appendix IV.

For use in "Corrections for Rounded

Edges and for Skin and Proximity Effects" in this paper, Figure 5 illustrates curves for the inductance of busses, comprised of indefinitely thin circular tubular conductor. It is interesting to note that these curves evidence the inductance of a bus comprised of thin square tubular conductors to be less than that of a bus comprised of thin circular tubular conductors having diameters equal to the sides of the corresponding square conductors.

Corroboration of the Approximate Equation

As a minor check on the correctness of equation 14, we note that if $a=c$ the conductors of Figure 4 are superimposed. As they carry equal currents in opposite directions, the bus vanishes electrically. Corroboratively, it is evident that $\lim_{a\to c}$ of the right-hand member of equation 14 is zero. A major simultaneous check on both equations 9 and 14 stems from noting that if in Figure 2 $b\to a$ and $d\to c$, we obtain a line-segment cross section as in Figure 4. Corroboratively, as detailed in Appendix V, $\lim_{d\to c}\lim_{b\to a}$ of the right-hand member of equation 9 yields the right-hand member of equation 14.

Inasmuch as the arguments and coefficients of the terms of right-hand members of equations 9, 14, 15, and 16 are without dimension, we note that in substituting in these equations, a, b, c, and d can be expressed in any like unit of length. But otherwise, the units of all quantities mentioned to this point are in the absolute system: bus dimensions in centimeters, current I in abamperes, and inductance L in abhenrys per centimeter of bus length. Multiplying abhenrys per centimeter by 3.048×10^{-3} yields millihenrys per foot of bus length; multiplying by 11.48×10^{-4} yields 60-cycle reactance in ohms per foot of bus length.

Some Illustrative Examples

To illustrate the use of the general formula and to gain knowledge of the accuracy to be expected of values calculated with the approximate formulas, we consider the following examples.

In example 1, the problem is to calculate the inductance of a coaxial bus comprised of two square tubular copper conductors: outer conductor, 6 inches square and 1/8 inch thick; inner conductor, 4 inches square and 3/16 inch thick.

Thus $a=6$, $b=23/4$, $c=4$, and $d=29/8$ inches. Substituting these values in equation 9, collecting and rearranging terms, obtaining values of the logarithmic and arctangentic terms from the Work Projects Administration tables, and effecting all calculations on a 10-row electric calculating machine yields*

$$L=0.75846_2 \text{ abhenry per centimeter of bus length} \quad (17)$$

Obviously, as by virtue of the assumptions underlying derivation of the general formula, it is unlikely that L represents the inductance of the bus to more than plus or minus several in the third decimal

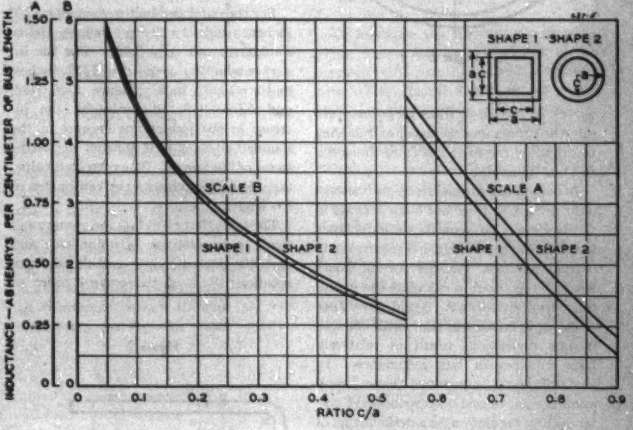


Figure 5

place, the last several digits have no physical significance. They are given to emphasize that, insofar as the numerical computation is concerned, the value of L is correct to the number of places indicated. For all logarithmic and arctangentic terms were taken to nine decimal places; values stemming from consequent arithmetic manipulations were held to the same number of decimals.

Inasmuch as the value given in the preceding equation stems from a final algebraic addition of some 32 terms, the largest of which approximates 300,000,000 and the smallest 89, it is essential that some such degree of preciseness be held. But, since the resulting value of L is significant to only two or three decimal places, it is not unlikely that a study of the number of decimal places to be held in the various stages of computation would reveal that a smaller number than actually used still would be satisfactory. However, inasmuch, as 15-place tables were employed and the calculation was performed on a 10-row electric calculating machine, the added labor is negligible, and there is no uncertainty as to the effect of cumulative errors on the accuracy of the first several digits of L.

In example 2, the problem is to calculate the inductance of a bus comprised of line-segment conductors having (1) the external, (2) the mean, and (3) the internal dimensions of the conductors of example 1:

1. $a=6.0$ inches, $c=4.0$ inches, $c/a=0.667$

2. $a=47/8$ inches, $c=61/16$ inches, $c/a=0.648$

3. $a=23/4$ inches, $c=29/8$ inches, $c/a=0.631$

For these values of c/a, we obtain from Figure 5:

1. $L_e=0.74$ abhenry per centimeter of bus length.

2. $L_m=0.80$ abhenry per centimeter of bus length.

3. $L_i=0.85$ abhenry per centimeter of bus length.

We note that the value 0.74, corresponding to the use of the external dimensions, and the value 0.758, calculated in example 1 by the use of the general formula, differ by only 2.4 per cent. This close agreement indicates that for the conditions which occur in practice (small conductor thicknesses, and ratio c/a not too near one) values of inductance sufficiently accurate for most design work can be calculated from the approximate formula by use of the external dimensions of the conductors. But since the approximate formula is epitomized in the

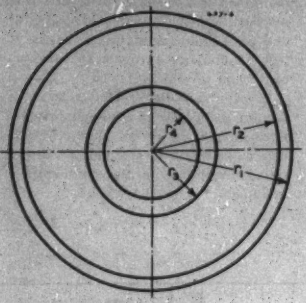


Figure 6

curves of Figure 5, from it we may obtain the inductance we need, only having to calculate the ratio c/a from the specified bus dimensions.

In consequence, considerable advantage with respect to time and labor accrues to the designer. To calculate the inductance from the curves of Figure 5 requires only several minutes, whereas several hours would be required to calculate the inductance from equation 9. Again, the values of example 2 indicate that small changes in bus dimensions result in relatively large changes in bus inductance. In that minimum inductance (hence minimum reactance and correspondingly better voltage regulation) is a desideratum of design, it behooves the designer to investigate all possible combinations of conductors (that are otherwise satisfactory) for the purpose of selecting that combination which possesses minimum inductance. But if the inductances of very many combinations had to be calculated from equation 9, the time, labor, and tedium involved would be considerable; on the other hand, the curves of Figure 5 enable evaluation in almost as many minutes as there are combinations to study.

Corrections for Rounded Edges and for Skin and Proximity Effects

Rounded Edges

To eliminate excessive edge heating caused by skin effect, square tubular conductors of commercial manufacture have rounded edges. Thus square tubular conductors of the sizes specified in example 1 have rounded edges of outer, inner, and mean radius indicated as follows:[19]

$a=6$ inches; $t=a-b=1/8$ inch; $r_o=3/4$ inch, $r_i=5/8$ inch, $r_m=11/16$ inch.

$c=4$ inches; $t'=c-d=3/16$ inch; $r_o=1/2$ inch, $r_i=5/16$ inch, $r_m=13/32$ inch.

Dwight and Wang[3] have derived, semi-empirically, that the approximate increase in inductance ΔL caused by rounding the edges of a conductor of square cross section is

$$\Delta L=2[k^2 \log k^{-1}+0.716k^2+0.5k^3+\ldots] \text{ abhenrys per centimeter of conductor length} \quad (18)$$

where $k=0.463r/s$, r is the mean radius of the rounded edge, s the mean side of the square cross section, and r is small compared with s, the accuracy increasing as $r/s \to 0$.

For the outer conductor, $s=a-t=47/8$ inches, and $r=11/16$ inch. Hence $k=0.0542$, and $\Delta L=0.022$. For the inner conductor, $s=c-t'=61/16$ inches, and $r=13/32$ inch. Hence $k=0.0494$, and $\Delta L=0.018$. Accordingly, the increase in bus inductance because of the rounded edges is 0.04 abhenry per centimeter of bus length. The corrected value, then, is 0.798 abhenry per centimeter of bus length.

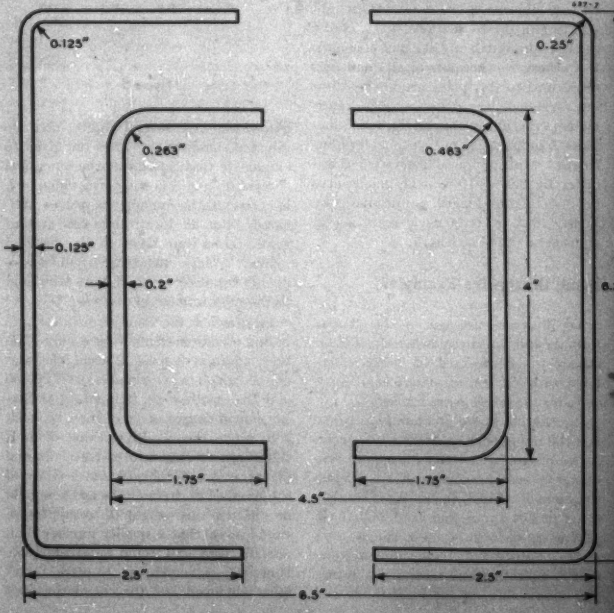
The facts that rounding the corners will result in an increase of inductance and that the increase just calculated from equation 18 is of the correct order of magnitude are confirmed by the following consideration of the coaxial bus with a cross section as shown in Figure 6. As derived in Appendix VI, the d-c inductance of this bus is

$$L=\{(r_3^3-3r_4^3)/2(r_3^3-r_4^3)+[2r_4^6/(r_3^3-r_4^3)^2] \log r_3/r_4\}+\{(r_2^3-3r_1^3)/2\times(r_1^3-r_2^3)+[2r_1^6/(r_1^3-r_2^3)^2]\times \log r_1/r_2\}+[2 \log r_2/r_3] \text{ abhenrys per centimeter of bus length} \quad (19)$$

where the first and second braced terms stem, respectively, from the flux-current linkages in the regions $r_4 \leq r \leq r_3$, and $r_2 \leq r \leq r_1$ (hence they are the so-called internal inductances of the inner and outer conductors) and the third braced term stems from the flux-current linkages in the region $r_3 \leq r \leq r_2$ (hence it is the so-called intra-inductance of the conductors). Let the conductors have (1) the same thicknesses and (2) external diameters equal to the external dimensions of the corresponding conductors of example 1. Thus $r_1=3$ inches, $r_3=23/8$ inches, $r_2=2$ inches, and $r_4=29/16$ inches. Substituting these values in equation 19 and performing the indicated computation yields

$$L=0.062+0.029+0.726$$
$$=0.817 \text{ abhenry per centimeter of bus length} \quad (20)$$

Figure 7



This value is a bit greater than the corrected value of 0.798 for rounded square conductors, which is to be expected. For as the radii of rounding increase, the coaxial square tubular bus approaches the coaxial circular tubular bus as a geometrical limit. Again, the magnitudes of the corrections for rounding increase with the radii of rounding. Hence it follows that the inductance of the square tubular bus approaches the inductance of the circular tubular bus as a limit and that the approach is from below.

In conclusion, it is to be noted that rounding of the edges, even if considerable, results in a relatively small increase in inductance, no matter what the sizes may be of the conductors comprising the bus. For a circular tubular conductor can be considered as the extreme case of a rounded square tubular conductor, its side being equal to the diameter of the circular conductor. Yet for all values of the independent variable of Figure 5, corresponding ordinates of the curves for the square and circular conductors differ by only a few per cent.

Skin and Proximity Effects

As the frequency increases from zero to a specified value, the currents in the inner and outer conductors of a coaxial circular tubular conductor tend to concentrate in thin surface strata on the adjacent surfaces of the two conductors. This phenomenon results in a decrease of the flux-current linkages in the regions $r_4 \leq r \leq r_3$, and $r_2 \leq r \leq r_1$. The flux-current linkages in the region $r_3 \leq r \leq r_2$ are, however, unchanged. The net result of the decrease in the internal inductances and of the constancy of the intra-inductance of the conductors is a decrease in the sum of the three, the total inductance of the bus. But, as in practical busses, the sum of the d-c internal inductances is, as evidenced in equation 20, only a few per cent of the total inductance, and as at 60-cycles the decrease in the internal inductances is only a fraction of one per cent of their d-c values, it follows that the actual change in total inductance caused by 60-cycle skin and proximity effects is negligible. Confirmatively, the authors have calculated the actual 60-cycle inductance of the circular tubular bus in a foregoing section ("Rounded Edges") and find it to be identical (to several places of decimals) with the d-c value cited in equation 20.

In view of the negligible change in the inductance of this coaxial circular tubular bus, the small two-per-cent difference between the inductance of this bus and the one of the coaxial rounded square tubular bus of example 1, and the general geometric similarity between these two busses, we conclude that in the bus of example 1, and in practical dimensioned rounded square tubular busses in general, 60-cycle skin and proximity effects are negligible insofar as the inductance of the bus is concerned. This conclusion is in accord with the results of analytic and experimental investigations of the inductance of coplanar busses comprised of square[9] tubular or rectangular[12] conductor.

Busses Comprised of Structural Tubular Conductor

A conductor comprised of two slightly separated channels or angles, placed flange to flange, usually is not of a square cross section. If, however, the cross section does not differ too greatly from a square cross section, and commonly this is the case in practice, it is to be expected that a fairly good approximation to the actual inductance of the bus can be effected by judicious use of the formulas for the square cross section. Thus for the bus dimensioned[2,3] as in Figure 7, consider an equivalent square tubular bus with conductors having the same external perimeters (rounded edges aside) as the ones in Figure 7. Then, as detailed in Appendix VII, the inductance of this equivalent bus is 0.755 abhenry per centimeter of bus length. Against this value we have the inductance, calculated (in Appendix VII) from the measured load impedance, as 0.837 abhenry per centimeter of bus length. The difference in the two values is approximately 10 per cent of the measured value. On the other hand, if we assume an equivalent bus having square conductors with sides equal to the webs of the given conductors, we obtain an inductance of 0.849 abhenry per centimeter of bus length. This value differs from the measured value by only 1.4 per cent. In general, we infer that selecting an equivalent bus on one or the other of the bases mentioned will yield an approximate value of inductance within a few per cent of the actual value, which is all that is required for most design purposes.

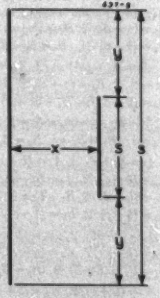


Figure 8

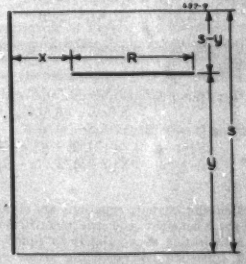


Figure 9

Polyphase Coaxial Busses

To calculate the performance of polyphase busses requires knowledge of the reactance drops on the individual conductors. The general equations for determining these reactance drops have been developed elsewhere.[4] It suffices here to mention that these equations express the reactance drops in terms of the self and mutual geometric mean distances of the cross sections of the square tubular conductors comprising the bus, and that these geometric mean distances are furnished by equation 8. For, as a comparison of equations 1 and 8 makes clear, in the right-hand member of equation 8 the first term is minus twice the logarithm of the self geometric mean distance of the outer hollow square of Figure 2, the second is minus twice the logarithm of the self geometric mean distance of the inner hollow square, and the third is four times the logarithm of the mutual geometric mean distance of the two hollow squares. Hence as a, b, c, and d are arbitrary, we have general formulas for the self and mutual geometric mean distances of two concentric parallel-sided hollow rectangles of arbitrary dimensions. In essence, therefore, calculation of the reactance drops on the conductors of a specified

polyphase bus reduces to determination of the numerical values of the required geometric mean distances from the just-mentioned formulas and substitution of these values in the general equations (which are typified by equation 28 of reference 8).

Appendix I

The geometric mean distances indicated in equation 8 follow from equation 3 by substitution therein of the following values of the parameters A_p and B_q, these values being obtained from equations 5 and 6 through inspection of Figure 2:

$\log D_{11}$: $A_1=A_2=B_1=B_2=a$; $A_3=A_4=B_3=B_4=0$

$\log D_{22}$: $A_1=A_2=B_1=B_2=b$; $A_3=A_4=B_3=B_4=0$

$\log D_{33}$: $A_1=A_2=B_1=B_2=c$; $A_3=A_4=B_3=B_4=0$

$\log D_{44}$: $A_1=A_2=B_1=B_2=d$; $A_3=A_4=B_3=B_4=0$

$\log D_{12}$: $A_1=A_2=B_1=B_4=(a+b)/2$; $A_3=A_4=B_2=B_3=(a-b)/2$

$\log D_{13}$: $A_1=A_4=B_1=B_3=(a+c)/2$; $A_2=A_3=B_2=B_4=(a-c)/2$

$\log D_{14}$: $A_1=A_2=B_1=B_2=(a+d)/2$; $A_3=A_4=B_3=B_4=(a-d)/2$

$\log D_{23}$: $A_1=A_4=B_1=B_4=(b+c)/2$; $A_2=A_3=B_2=B_3=(b-c)/2$

$\log D_{24}$: $A_1=A_4=B_1=B_3=(b+d)/2$; $A_2=A_3=B_2=B_4=(b-d)/2$

$\log D_{34}$: $A_1=A_2=B_1=B_2=(c+d)/2$; $A_3=A_4=B_3=B_4=(c-d)/2$

Utilizing these parameters in equation 3 yields

$$S_1^2 \log D_{11} = -(25/12)S_1^2 - (1/6)[K(a,a) + K(0,0) - 2K(a,0)] \quad (21)$$

$$S_1 S_2 \log D_{12} = -(25/12)S_1 S_2 - (1/6)\times [K[(a+b)/2,(a+b)/2] + K[(a-b)/2,(a-b)/2] - 2K[(a+b)/2,(a-b)/2]] \quad (22)$$

and similar obvious equations are obtained for the other eight geometric mean distances.

Substituting appropriately in equation 8 and collecting corresponding terms in K yield

$$L = [-1/3(a^2-b^2)^2]\{2K[(a+b)/2,(a+b)/2] + 2K[(a-b)/2,(a-b)/2] - 4K[(a+b)/2,(a-b)/2] - K(a,a) - K(b,b) + 2K(a,0) + 2K(b,0)\} + [-1/3(c^2-d^2)^2]\{2K[(c+d)/2,(c+d)/2] + 2K[(c-d)/2,(c-d)/2] - 4K[(c+d)/2,(c-d)/2] - K(c,c) - K(d,d) + 2K(c,0) + 2K(d,0)\} + [2/3(a^2-b^2)(c^2-d^2)]\{K[(a+d)/2,(a+d)/2] + K[(a-d)/2,(a-d)/2] - 2K[(a+d)/2,(a-d)/2] - K[(b+d)/2,(b+d)/2] - K[(b-d)/2,(b-d)/2] + 2K[(b+d)/2,(b-d)/2] - K[(a+c)/2,(a+c)/2] - K[(a-c)/2,(a-c)/2] + 2K[(a+c)/2,(a-c)/2] + K[(b+c)/2,(b+c)/2] + K[(b-c)/2,(b-c)/2] - 2K[(b+c)/2,(b-c)/2]\} \quad (23)$$

Evaluating the various terms through the use of equation 4 yields equation 9.

As already discussed in an earlier part of this paper ("Polyphase Coaxial Busses"), the terms of the right-hand members of equation 9, and thus of equation 23, can be interpreted in terms of the self and mutual geometric mean distances of the two hollow rectangles of Figure 2.

Appendix II

The geometric mean distances indicated in equation 11 follow from equation 3 by substitution therein of the following values of the parameters A_p and B_q, these values being obtained from equations 5 and 6 through inspection of Figure 3:

$\log D_{11}$: $A_1=A_2=a$, $A_3=A_4=0$; $B_1=B_2=(a-b)/2$, $B_3=B_4=0$

$\log D_{22}$: $A_1=A_2=a$, $A_3=A_4=0$; $B_1=B_2=b$, $B_3=B_4=0$

$\log D_{33}$: $A_1=A_2=c$, $A_3=A_4=0$; $B_1=B_2=(c-d)/2$, $B_3=B_4=0$

$\log D_{44}$: $A_1=A_2=(c-d)/2$, $A_3=A_4=0$; $B_1=B_2=d$, $B_3=B_4=0$

$\log D_{12}$: $A_1=(a-b)/2$, $A_2=0$, $A_3=a$, $A_4=(a+b)/2$; $B_1=(a+b)/2$, $B_2=b$, $B_3=0$, $B_4=(a-b)/2$

$\log D_{13}$: $A_1=A_2=a$, $A_3=A_4=0$; $B_1=a$, $B_2=B_4=(a+b)/2$, $B_3=b$

$\log D_{23}$: $A_1=A_2=(a+c)/2$, $A_3=A_4=(a-c)/2$; $B_1=(a-d)/2$, $B_2=(b-d)/2$, $B_3=(b-c)/2$, $B_4=(a-c)/2$

$\log D_{14}$: $A_1=(a-d)/2$, $A_2=(a+d)/2$, $A_3=(a+c)/2$, $A_4=(a-c)/2$; $B_1=(a+d)/2$, $B_2=(b+d)/2$, $B_3=(b-d)/2$, $B_4=(a-d)/2$

$\log D_{17}$: $A_1=A_2=(a+c)/2$, $A_3=A_4=(a-c)/2$; $B_1=(a+c)/2$, $B_2=(b+c)/2$, $B_3=(b+d)/2$, $B_4=(a+d)/2$

$\log D_{24}$: $A_1=a$, $A_2=A_4=(a+b)/2$, $A_3=b$; $B_1=B_3=b$, $B_2=B_4=0$

$\log D_{28}$: $A_1=(a+c)/2$, $A_2=(b+c)/2$, $A_3=(b-c)/2$, $A_4=(a-c)/2$; $B_1=(b-d)/2$, $B_2=(b+d)/2$, $B_3=(b+c)/2$, $B_4=(a+c)/2$

$\log D_{34}$: $A_1=(a-d)/2$, $A_2=A_4=(b+d)/2$, $A_3=(b-d)/2$; $B_1=B_2=(b+d)/2$, $B_3=B_4=(b-d)/2$

$\log D_{12}$: $A_1=(a+c)/2$, $A_2=(b+c)/2$, $A_3=(b+d)/2$, $A_4=(a+d)/2$; $B_1=B_2=(b+d)/2$, $B_3=B_4=(b-d)/2$

$\log D_{56}$: $A_1=(c-d)/2$, $A_2=(c+d)/2$, $A_3=c$, $A_4=0$; $B_1=(c+d)/2$, $B_2=d$, $B_3=0$, $B_4(c-d)/2$

$\log D_{57}$: $A_1=A_2=c$, $A_3=A_4=0$; $B_1=c$, $B_2=B_4=(c+d)/2$, $B_3=d$

$\log D_{58}$: $A_1=c$, $A_2=A_4=(c+d)/2$, $A_3=d$; $B_1=B_3=d$, $B_2=B_4=0$

Substituting these parameters in equation 3 yields, in terms of K, the desired expressions for the geometric mean distances (which have been omitted here because of the space required). Substituting these expressions in equation 11 and collecting like terms yields equation 23 and hence, corroboratively, equation 9.

Appendix III

The geometric mean distance between two line segments, located as illustrated in Figure 8, is given by equation 11 of reference 9:

$$S_3 \log D = (1/2)\{-[x^2-(S+y)^2]\times \log[x^2+(S+y)^2]+(x^2-y^2)\times \log(x^2+y^2)+4x(S+y)\times \tan^{-1}[(S+y)/x]-4xy\times \tan^{-1}(y/x)-3S_3\} \quad (24)$$

The geometric mean distance between two line segments, located as illustrated in Figure 9, is given by equation 15 of reference 9:

$$R_3 \log D = I(R+x,s-y)-I(x,s-y)+I(R+x,y)-I(x,y)-3R_3/2 \quad (25)$$

wherein, typically,

$$I(x,y) = (1/2)[xy\log(x^2+y^2)+x^2\times \tan^{-1}(y/x)+y^2\tan^{-1}(x/y)] \quad (26)$$

The geometric mean distances indicated in equation 13 are obtained by substitution in equation 24 of the first six, and in equation 25 of the last three, of the following sets of values of the parameters x, y, R, and S, these values being obtained by inspection of Figures 4, 8, and 9:

$\log D_{11}$: $x=0$, $y=0$, $S=s=a$

$\log D_{22}$: $x=0$, $y=0$, $S=s=c$

$\log D_{12}$: $x=a$, $y=0$, $S=s=a$

$\log D_{37}$: $x=c$, $y=0$, $S=s=c$

$\log D_{15}$: $x=y=(a-c)/2$, $S=c$, $s=a$

$\log D_{17}$: $x=(a+c)/2$, $y=(a-c)/2$, $S=c$, $s=a$

$\log D_{12}$: $x=0$, $y=0$, $R=s=a$

$\log D_{34}$: $x=0$, $y=0$, $R=S=c$

$\log D_{13}$: $x=(a-c)/2$, $y=(a+c)/2$, $R=c$, $s=a$

Utilizing these parameters in equations 24 and 25 as stated yields

$\log D_{11} = \log a - 3/2$

$\log D_{22} = \log c - 3/2$

$\log D_{12} = \log a + (1/2)\log 2 + \pi/4 - 3/2$

$\log D_{34} = \log c + (1/2)\log 2 + \pi/4 - 3/2$

$\log D_{15} = \log a + \pi/2 - 3/2$

$\log D_{37} = \log c + \pi/2 - 3/2$

$\log D_{13} = (1/2)\{\log(a^2+c^2) + [(a^2-c^2)/ac]\times \tan^{-1}[(a+c)/(a-c)] - \pi(a-c)^2/4ac - 3\}$

$\log D_{18} = (1/4)\{[(a+c)^2/ac]\log(a+c) - [(a-c)^2/ac]\log(a-c) - 2\log 2 + \pi - 6\}$

$\log D_{17} = (1/2)1\{\log(a^2+c^2) - [(a^2-c^2)/ac]\times \tan^{-1}[(a-c)/(a+c)] + \pi(a+c)^2/4ac - \log 2 - 3\}$

Appendix IV

The co-ordinates used for plotting the curves of Figure 5 for the square tubular conductors are obtained by substituting the indicated values of A in equation 16, obtaining the values of the logarithmic and arctangentic terms from the Work Projects Administration tables, and performing all computation on a 10-row electric calculating machine. To avoid cumulative errors all

computation was effected to eight significant figures. For actual plotting, however, the inductance need only be known to the three or four significant figures given in Table I.

Table I

A	r=c/a	L	A	r=c/a	L
0	1	0	0.6	1/4	2.693
0.1	9/11	0.354	0.7	3/17	3.389
0.2	2/3	0.744	0.8	1/9	4.315
0.3	7/13	1.164	0.9	1/19	5.809
0.4	3/7	1.617	1.0	0	∞
0.5	1/3	2.117			

The inductance of a coaxial bus comprised of indefinitely thin circular tubular conductors, dimensioned as in shape 1 of Figure 5, is $L=-2\log(c/a)$. Hence the co-ordinates of the curves of Figure 5 for shape 1 are as shown in Table II.

Table II

c/a	L	c/a	L	c/a	L
0	∞	0.4	1.833	0.8	0.373
0.1	4.605	0.5	1.386	0.9	0.193
0.2	3.219	0.6	1.022	1.0	0
0.3	2.408	0.7	0.728		

Appendix V

Equation 23 for the inductance of a bus, with a cross section as illustrated in Figure 2 is valid for conductors of arbitrary thickness. Accordingly, the inductance of a bus with a cross section comprised of line segments as shown in Figure 4 can be obtained by determining the limit of the inductance of the bus in Figure 2 as the thicknesses of the conductors comprising the bus approach zero.

To effect this determination, we require, as will be seen below, knowledge of the following derivatives: $\partial^2K(u,u)/\partial x^2$, $\partial^2K(v,v)/\partial y^2$, $\partial^2K(u,v)/\partial x\partial y$, wherein $u=(x+y)/2$, and $v=(x-y)/2$. From equation 4 we have

$$K(u,u)=-4u^4\log u-2u^4\log 2-2u^4\pi \quad (27)$$

Substituting from equation 27 into the identity

$$\frac{\partial^2K(u,u)}{\partial y\partial x}=\frac{\partial}{\partial u}\left[\frac{\partial K}{\partial x}\frac{\partial u}{\partial x}\right]\frac{\partial u}{\partial y} \quad (28)$$

and performing the indicated differentiations yield

$$\partial^2K(u,u)/\partial y\partial x=-u^2(12\log u+6\log 2+6\pi+7) \quad (29)$$

Hence

$$\partial^2K[(x+y)/2,\ (x+y)/2]/\partial y\partial x=-[(x+y)^2/4][12\log(x+y)-6\log 2+6\pi+7] \quad (30)$$

Similarly,

$$\partial^2K[(x-y)/2,\ (x-y)/2]/\partial y\partial x=[(x-y)^2/4][12\log(x-y)-6\log 2+6\pi+7] \quad (31)$$

To evaluate $\partial^2K(u,v)/\partial x\partial y$ we note that the real part of the complex function

$$W(w)\equiv W(u+iv)=U(u,v)+iV(u,v)=w^4\log w \quad (32)$$

is

$$Re(W)=U(u,v)=K(u,v)+2\pi uv^3 \quad (33)$$

This identity is easily established by separating $w^4\log w$ into its real and imaginary parts and using the identity $\tan^{-1}u/v+\tan^{-1}v/u=\pi/2$. Now

$$\frac{\partial^2U}{\partial x\partial y}=\frac{\partial^2U}{\partial u^2}\frac{\partial u}{\partial x}\frac{\partial u}{\partial y}+\frac{\partial^2U}{\partial v^2}\frac{\partial v}{\partial x}\frac{\partial v}{\partial y}+\frac{\partial^2U}{\partial u\partial v}\left[\frac{\partial v}{\partial x}\frac{\partial u}{\partial y}+\frac{\partial u}{\partial x}\frac{\partial v}{\partial y}\right]+\frac{\partial U}{\partial u}\frac{\partial^2u}{\partial x\partial y}+\frac{\partial U}{\partial v}\frac{\partial^2v}{\partial x\partial y} \quad (34)$$

Inasmuch as

$$d^3W/dw^3=\partial^3U/\partial u^3+i\partial^3V/\partial u^3=-\partial^3U/\partial v^3-i\partial^3V/\partial v^3 \quad (35)$$

we have $\partial^3U/\partial u^3=-\partial^3U/\partial v^3=Re(d^3W/dw^3)$. Accordingly, substituting appropriately in equation 34 and performing the indicated differentiations with respect to x and y gives

$$\partial^2U/\partial x\partial y=(1/4)[Re(d^3W/dw^3)+Re(d^3W/dw^3)+0+0+0]=1/2Re(d^3W/dw^3) \quad (36)$$

Substituting from equation 32 in equation 36 and performing the indicated differentiation yields

$$\partial^2U/\partial x\partial y=Re(6w^2\log w+7w^2/2)=Re[6(u^2-v^2+2iuv)\log(u+iv)+7(u^2-v^2+2iuv)/2]=3(u^2-v^2)\log(u^2+v^2)-12uv\times\tan^{-1}v/u+7(u^2-v^2)/2 \quad (37)$$

Since, from equation 33,

$$\partial^2K/\partial x\partial y=\partial^2U/\partial x\partial y-2\pi\partial^2(uv^3)/\partial x\partial y \quad (38)$$

we obtain, on substitution in equation 38 from equation 37 and expressing u and v in terms of x and y,

$$\partial^2K[(x+y)/2,\ (x-y)/2]/\partial x\partial y=3xy\times\log(x^2+y^2)-3xy\log 2-3(x^2-y^2)\times\tan^{-1}[(x-y)/(x+y)]+7xy/2+3\pi(x^2-y^2)/4 \quad (39)$$

With these identities obtained, we are prepared to consider the limiting process. For convenience, equation 9 is written in the form

$$L=(-1/3)L_1(a,b)/(a^2-b^2)^2-(1/3)L_2\times(c,d)/(c^2-d^2)^2+(2/3)L_3(a,b,c,d)+(a^2-b^2)(c^2-d^2) \quad (40)$$

First, let $b\to a$. In the limit the outer conductor of Figure 2 is comprised of line segments. The inductance of the resulting bus is

$$\lim_{b\to a}L=(-1/3)\lim_{b\to a}L_1(a,b)/(a^2-b^2)^2-(1/3)L_2(c,d)/(c^2-d^2)^2+(2/3)\lim_{b\to a}L_3(a,b,c,d)/(a^2-b^2)\times(c^2-d^2) \quad (41)$$

Now $[L_1(a,b)/(a^2-b^2)^2]_{b=a}=0/0$; similarly $[L_3(a,b,c,d)/(a^2-b^2)(c^2-d^2)]_{b=a}=0/0$. Accordingly, the limits in the right-hand member of equation 41 are to be determined by applying L'Hospital's rule for evaluating indeterminate expressions of the form 0/0. Applying this rule to the first limit yields

$$\lim_{b\to a}L_1(a,b)/(a^2-b^2)^2=\{[\partial^2L_1(a,b)/\partial^2b]+[\partial^3(a^2-b^2)/\partial^3b]\}_{b=a} \quad (42)$$

A second differentiation of numerator and denominator is necessary because the ratio of the first derivatives (for $b=a$) is also of the form 0/0. Performing the differentiations and substitutions indicated gives

$$(1/3)\lim_{b\to a}L_1(a,b)/(a^2-b^2)^2=2\log a+(1/2)\log 2+\pi/2+7/6 \quad (43)$$

For the second limit, L'Hospital's rule yields

$$\lim_{b\to a}L_3(a,b,c,d)/(a^2-b^2)(c^2-d^2)=\{[\partial L_3(a,b,c,d)/\partial b]/[\partial(a^2-b^2)\times(c^2-d^2)/\partial b]\}_{b=a} \quad (44)$$

Effecting the differentiations and substitutions indicated gives

$$\lim_{b\to a}L_3(a,b,c,d)/(a^2-b^2)(c^2-d^2)=L'_3(a,c,d)/(-2a)(c^2-d^2) \quad (45)$$

wherein

$$L'_3(a,c,d)=[\partial]-K[(a+d)/2,\ (a+d)/2]-K[(a-d)/2,\ (a-d)/2]+2K[(a+d)/2,\ (a-d)/2]+K[(a+c)/2,\ (a+c)/2]+K[(a-c)/2,\ (a-c)/2]-2K[(a+c)/2,\ (a-c)/2]\}/\partial b]_{b=a} \quad (46)$$

Secondly, let $d\to c$. In the limit the inner conductor of Figure 2 is comprised of line segments, hence the cross section is now that of Figure 4. From equations 41, 43, and 45, the inductance of this line segment bus is

$$\lim_{d\to c}\lim_{a\to b}L=-[2\log a+(1/2)\log 2+\pi/2+7/6]-(1/3)\lim_{d\to c}L_3(c,d)+(c^2-d^2)^2+(2/3)\lim_{d\to c}L'_3(a,c,d)+(-2a)(c^2-d^2) \quad (47)$$

Except for the interchange of a and b with c and d, the second term in the right-hand member of equation 47 is identical with the first term in the right-hand member of equation 41. Hence from equation 43, we have

$$(1/3)\lim_{d\to c}L_3(c,d)/(c^2-d^2)^2=2\log c+(1/2)\log 2+\pi/2+7/6 \quad (48)$$

Now

$$[L'_3(a,c,d)/(-2a)(c^2-d^2)]_{c=d}=0/0$$

Accordingly, L'Hospital's rule yields

$$\lim_{d\to c}L'_3(a,c,d)/(-2a)(c^2-d^2)=\{[\partial L'_3(a,c,d)/\partial d]/[\partial(-2a)\times(c^2-d^2)/\partial d]\}_{d=c}=L''_3(a,c)/4ac \quad (49)$$

wherein

$$L''_3(a,c)=[\partial^2]-K[(b+d)/2,\ (b+d)/2]-K[(b-d)/2,\ (b-d)/2]+2K[(b+d)/2,\ (b-d)/2]/\partial d\partial b]_{\substack{b=a\\d=c}} \quad (50)$$

Performing the differentiations by use of equations 30, 31, and 39 and substituting as indicated yields

$$(1/3)L''_s(a,c)/4ac = -(a/4c)\log[(a-c)+(a+c)]-(c/4a)\log[(a-c)/(a+c)]+(1/2)\log[(a^3-c^3)(a^3+c^3)]-[(a^3-c^3)/2ac]\tan^{-1}[(a-c)+(a+c)]+\pi(a^3-c^3)/8ac-\log 2+\pi/2+7/6 \quad (51)$$

Finally, substituting from equations 48 and 49 in equation 47 and collecting terms yields, corroboratively, equation 14.

Appendix VI

By virtue of the fundamental definition of the inductance of a circuit, $L=W/2I^2$, wherein W is the energy in the magnetic field produced by the circuit current I, and the calculation of L reduces to the calculation of W. Because of the circular symmetry of the coaxial circular tubular bus with a cross section as illustrated in Figure 6, W easily is calculated from the well-known relation $W=1/2$ (summation of the flux-current linkages associated with the circuit). Accordingly, $L=$(summation of the flux-current linkages)$/I^2$.

In that a circular tubular conductor produces no field in the cylindrical space bounded by its internal surface, the flux density B, and thus the flux-current linkage, in the region $0\geq r\geq r_4$ is zero.

In the region $r_4\geq r\geq r_3$, we have $B=2\mu\, I(r)/r$, wherein $I(r)=I(r^2-r_4^2)/(r_3^2-r_4^2)$ is the current in the region $r_4\geq r\geq r$. Accordingly, the flux contained in a thin tube of unit length and of thickness dr is $[2\mu\, I(r)dr/r]$. Hence the total flux-current linkages per unit length are

$$[2\mu I^3/(r_3^2-r_4^2)^2]\int_{r_4}^{r_3}[(r^2-r_4^2)/r]dr = [2\mu I^3/(r_3^2-r_4^2)^2][(r_3^2-r_4^2)\times(r_3^2-3r_4^2)/4+r_4^2\log(r_3/r_4)] \quad (52)$$

In the region $r_3\geq r\geq r_2$, the flux density is $B=2\mu I/r$, the flux contained in a thin tube of unit length and of thickness dr is $(2\mu I/r)dr$, and the current encompassed by this flux is I. Hence the total flux-current linkages are

$$2\mu I^2\int_{r_3}^{r_2}(1/r)dr = 2\mu I^2\log(r_2/r_3) \quad (53)$$

In the region $r_2\geq r\geq r_1$, we have $B=2\mu I(r)/r$; hence the flux contained in a thin tube of unit length and of thickness dr is $2\mu I(r)/dr$. The current encompassed by this flux is $I(r)=I-I(r^2-r_2^2)/(r_1^2-r_2^2)=I(r_1^2-r^2)/(r_1^2-r_2^2)$. Thus the total flux linkages are

$$[2\mu I^3/(r_1^2-r_2^2)^2]\int_{r_2}^{r_1}[(r_1^2-r^2)/r]dr = [2\mu I^3/(r_1^2-r_2^2)^2][(r_1^2-r_2^2)\times(r_2^2-3r_1^2)/4+r_1^2\log(r_1/r_2)] \quad (54)$$

The total of the flux-current linkages is the sum of the right-hand members of equations 52, 53, and 54. Dividing this sum by I^2 and taking $\mu=1$ yield the right-hand member of equation 19.

Appendix VII

The external perimeters of the cross sections of the outer and inner conductors of Figure 7 are encompassed by rectangles respectively 25.5 inches and 17 inches in perimeter. Consider equivalent conductors of square cross section, of external perimeters equal to these values, and of the same thicknesses as the given conductors. The external, mean, and internal ratios of c/a are, respectively, 0.667, 0.648, and 0.629. From Figure 5 we obtain, respectively, 0.74, 0.80, and 0.855 abhenry per centimeter of bus length. Again, $r_e=0.1875$ and $r_i=0.363$, thus $k_e=0.0134$ and $k_i=0.0415$. Hence from equation 18, we obtain respectively 0.0019 and 0.0134 abhenry per centimeter of bus length as corrections for the rounding of the edges of the outer and inner conductors. Accordingly, the total inductance of the equivalent bus, depending on the dimensions used, is

$$L_e=0.755;\quad L_m=0.815;\quad L_i=0.87 \text{ abhenry per centimeter of bus length} \quad (55)$$

On the other hand, if we assume the equivalent bus to be comprised of conductors with sides of 6.25 inches and 4 inches, the dimensions of the webs of the corresponding given conductors, the corresponding ratios of c/a are 0.641, 0.621, and 0.600. From Figure 5 we obtain respectively 0.825, 0.885, and 0.938 abhenry per centimeter of bus length. Again, $k_e=0.0142$ and $k_i=0.0442$, hence from equation 18 we obtain respectively 0.002 and 0.015 abhenry per centimeter of bus length as corrections for the rounding of the edges of the outer and inner conductors. Accordingly, the total inductance of the equivalent bus, depending on the dimensions used, is

$$L_e=0.842;\quad L_m=0.902;\quad L_i=0.950 \text{ abhenry per centimeter of bus length} \quad (56)$$

Though for comparison values of L_e, L_m, and L_i are displayed, the results in the previous section "Some Illustrative Examples" indicate that the external value would be used for actual computation. In such case, calculation of edge corrections is simplified by use of the external rather than the mean dimensions indicated in equation 18. Proceeding thus for the bus equivalent on the basis of webs yields 0.024 rather than 0.017. The difference in these two values is negligible in comparison with the total inductance. Further, as the correction increases, the calculation is on the safe side.

The a-c resistance of the actual bus is

$$R=\rho(A_e^{-1}+A_i^{-1})K_s \text{ ohms per foot of bus length} \quad (57)$$

wherein ρ is the resistivity (in ohms-circular mils per foot) of the copper at operating temperature, A_e and A_i are the areas (in circular mils) of the cross sections of the outer and inner conductors, and K_s is the skin effect factor of the conductors.

In the absence of stated experimental values, we assume conventional values of 50 degrees centigrade for the operating temperature and 98 per cent conductivity for the bus copper. Then the resistivity is $\rho=(10.37/0.98)[1+0.00393(50-20)]=11.82$ ohms-circular mils per foot. The outer conductor, constructed of two rectangular strips bent into shape, is of area $A_e=2(10.75\times0.125)=2.69$ square inches, thus 3,430,000 circular mils. The inner conductor, comprised of stock channels, is of area $A=2[2(1.75-0.463)0.2+(4-2\times0.463)0.2+\pi(0.463^2-0.263^2)/2]=2.72$ square inches, thus 3,460,000 circular mils. The skin-effect factor[12] for a range of square tubular conductors, which encompasses those approximating the shapes of the given conductors, is $K_s=1.04$.

Substituting these values in equation 57 yields a resistance of 7.18 micro-ohms per foot of bus length. The measured impedance is 12 micro-ohms per foot of bus length. From this value we find the inductance to be $L=(144-51.3)^{1/2}/377=2.55$ microhenrys, or in centimeter-gram-second units, 0.837 abhenry per centimeter of bus length.

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Supervisory Control of 30,000-Kva Hydroelectric Plant

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Synopsis: Ocoee 3, a 1-unit 30,000-kva supervisory-controlled generating station of the Tennessee Valley Authority, has been in operation since April 30, 1943. An underground cable was selected for the control and telemetering channel, and neutralizing transformers were installed to protect against voltage rise resulting from transmission line faults. Instrumentation, controls, and station auxiliaries were designed particularly to safeguard the unattended equipment. Maintenance includes two or three inspections per week. The cost of supervision, operation, and maintenance is as low as $0.101 per 1,000 kilowatt-hours.

THE AUTOMATIC and supervisory control features of Ocoee 3 hydroelectric plant of the Tennessee Valley Authority are of special interest because of the size and importance of the equipment controlled. The 30,000-kva generator is one of the large units in the United States operating completely unattended, and the outdoor switchyard with its 74,000-kva 161/69/13.8-kv tap-changing-under-load transformer bank serves as a switching center for the 154- and 66-kv transmission lines in the area. The entire plant is supervisory-controlled from Ocoee 2 hydroelectric plant located five miles downstream.

The geographical location and transmission line connections of Ocoee 3 plant are shown in Figure 1. The 154-kv line to Apalachia serves as a tie between the main 154-kv transmission system and the local 66-kv transmission system in the Ocoee River area. The installed generating capacities of Ocoee 2 and Blue Ridge hydroelectric plants, which are connected to the 66-kv system, are 19,900 and 20,000 kw respectively.

Ocoee 3 Dam is located 2.5 miles upstream from the powerhouse, and a connecting tunnel terminates in a surge tank at the upper end of the penstock. A butterfly valve is provided in the penstock near the surge tank. A view of the surge tank, valve house, penstock, powerhouse, and switchyard is shown in Figure 2.

A single-line diagram of the Ocoee 3 main electrical connections and the principal metering and relaying connections is shown in Figure 3. No additional generating units are to be installed in the future, but provision is made in the design for an ultimate of two 154-kv lines and four 66-kv lines.

From the system operating standpoint, it would be preferable to have Ocoee 2 plant supervisory-controlled from Ocoee 3, but this was impractical because of the unsuitability for automatic operation of the equipment in Ocoee 2 plant, which was built in 1913. It was felt that for successful remote operation without undue interruptions for minor troubles, all control features of the major equipment should be selected specially for nonattended operation, and this dictated that Ocoee 3 plant should be the controlled plant with the dispatcher's board located at Ocoee 2.

Control and Telemetering Channels

In selecting the type of channels to be used for the control and metering circuits between Ocoee 3 and Ocoee 2, three possibilities were explored: leased wire from the local telephone company, carrier current, and an overhead or underground cable between the two plants. All forms of open-wire construction were rejected as not being sufficiently reliable, and this decision eliminated the use of leased-wire facilities since only open-wire lines were available from the local telephone company. Carrier channels, while probably somewhat less expensive than an underground cable installation, were rejected because of the limited number of channels obtainable without undue complication and the feeling that at the present state of the art there would be some sacrifice in reliability and increase in maintenance with the use of carrier. The length of the channel, only six miles, was just short enough that the attractive economies of carrier channels over metallic wire channels could not be realized unless the number of channels was reduced to the absolute minimum. Overhead armored cable was considered seriously but decided against. It would have been necessary to follow the highway to avoid rough mountain terrain, and with the highway route, the hazard of malicious damage, rock slides, and traffic accidents made this scheme undesirable. Underground cable was selected finally because it was expected that it would provide practically trouble-free service with the minimum of maintenance and the maximum number of completely independent channels.

The underground cable installed consists of a 51-pair number 19-American-wire-gauge double-paper-insulated lead-covered tape-armored telephone cable with jute covering for subterranean service. The cable is similar to standard telephone cable except that the withstanding voltage from conductors to sheath is 3,500 volts, 60 cycles for 20 seconds, this being approximately double the voltage rating ordinarily used for telephone service. The cable is buried along the edge of the state highway between the plants, with manholes at each splice point spaced approximately 3,000 feet apart. The cable is gas-filled and maintained under 8-pound pressure to prevent the entrance of moisture. Pressure switches are installed in the cable at every third manhole and connected to one of the cable pairs to operate an annunciator at Ocoee 2 in the event of a break in the cable sheath and consequent loss of gas pressure. The allocation of cable pairs is shown in Table I.

Table I

No. of Pairs	Service
2	Supervisory control
23	Metering
4	Direct-wire control and pilot-wire relaying
1	Printing annunciator
8	Communication (includes TVA system communication other than for Ocoee 3)
13	Spare
51	Total

Control Cable Protection

Experience with remote-control and communication cables at a number of TVA plants had demonstrated that extraneous voltages appear on the cable conductors during phase-to-ground faults on the transmission system. With the cables enclosed in metallic sheaths and buried underground, induced voltages are avoided, but serious voltages do result from a rise of station ground potential above remote ground potential. They ap-

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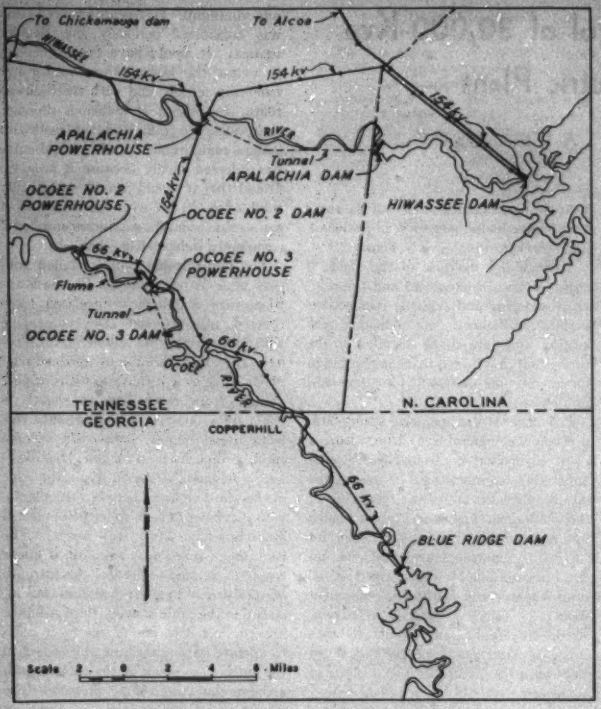

Figure 1. Location and transmission connections

pear across the cable insulation and across the protector gaps at the cable terminals. At plants where large neutral currents are allowed to flow, the extraneous voltages may become excessive and render the circuits inoperative at a time when they are most needed.

Investigation indicated that at the Ocoee plants, excessive voltages caused by the rise of station ground potential were a probability. Although one of the most effective methods of reducing the rise of station ground potential is to reduce the station ground resistance, low ground resistance was extremely difficult to obtain at the Ocoee plants because both plants are located in a mountainous region with deep rock formations underlying a comparatively thin layer of topsoil. The final tested ground resistance at Ocoee 3 was 0.5 ohm, while at Ocoee 2 the lowest value which it was practicable to obtain was 1.4 ohms. With these values of ground resistance, the calculated rise of station ground potential above remote ground for maximum ground fault current in the transformer bank neutrals was considerably in excess of the rating of the protectors. Special measures therefore had to be taken at both plants either to limit or to compensate for the rise in station ground potential.

At Ocoee 3 a 5.5-ohm grounding reactor was installed in the 66-kv neutral of the transformer bank to reduce the maximum neutral short-circuit current. The reactor is of the outdoor oil-insulated type. It reduces the maximum 66-kv neutral fault current from 4,300 to 2,600 amperes, with a corresponding reduction in the rise of the Ocoee 3 ground potential.

A similar solution could not be used at Ocoee 2 because the insulation of the old transformers at this plant is suitable for solidly grounded operation only. The protective measures adopted consisted of installing neutralizing transformers to compensate for the difference in ground potentials. The neutralizing transformers are of the 3-winding type, with the two secondaries of each transformer connected in the conductors of a cable pair and the primary connected between the cable sheath and ground. By keeping the cable sheath at remote ground potential, the difference in ground potential is impressed on the primary winding, thus introducing a compensating voltage in the conductors so that the conductors on the cable side of the neutralizing transformers are at remote ground or sheath potential while on the station side of the neutralizing transformers the conductors are at station ground potential. Obviously, it was necessary to keep the cable sheath and armor free from the influence of the Ocoee 2 station ground potential. To accomplish this, it was not considered practicable to provide an insulating covering over the sheath and armor which would not be subject to rather rapid deterioration; therefore, the cable was brought out of the ground at a point approximately 500 feet from the Ocoee 2 powerhouse and run overhead on poles to the neutralizing transformers.

The neutralizing transformers are indoor-type rated 4,000 volts and are installed in a weatherproof box mounted on a pole structure near Ocoee 2 powerhouse.

Supervisory Control Equipment

The selection of a multiconductor cable for the control channels between the plants permitted an unrestricted choice of the several types of supervisory control equipment available, since it was not necessary to keep the number of conductors required for the control channel to an absolute minimum. Had it been necessary to limit the control channel to two wires, the selection of supervisory control equipment would have been restricted to the type in which all operations are performed by coded impulsing. While this type has been successfully used in smaller installations on the TVA system, it was felt that the large amount and variety of complicated controls involved at Ocoee 3 justified utilizing any simplification which could be obtained in the supervisory control equipment itself.

Accordingly, a type of supervisory system requiring four instead of two line wires was selected. This equipment is essentially a direct-wire system of control and indication with step-type selector relays which transfer the line wires from one circuit to another. After the transfer is made, all operation of the equipment is done directly through auxiliary relays without further impulsing. Two standard 23-point units are installed, of which 30 points are used initially and the remaining

Table II

No. of Supervisory Points	Type of Service	Description
5	Control and indication	13.8-, 66-, and 154-kv oil circuit breaker control
5	Control and indication	13.8-, 66-, and 154-kv motor-operated disconnecting switch control
3	Control and indication	Automatic - manual selection for transformer tap-changing, generator voltage regulator, and generator starting and stopping
8	Control and indication	Metering selection
2	Control and indication	Generating unit automatic start-stop and penstock butterfly valve emergency close
5	Control only	Raise-lower control for gate limit adjustment, transformer tap-changing, generator voltage adjusting rheostat, and exciter field rheostat and potentiometer telemetering calibration
2	Indication only	Lock-out relay position and generator breaker tripping bus indication
16		Spare
46	Total	

Table III

No. of Transmitters and Receivers	Type	Service
3	Torque balance	Generator amperes, kilowatts, and kilovars
4	Torque balance	Transformer 154- and 66-kv amperes, kilowatts, and kilovars
2	Torque balance	66-kv line amperes, kilowatts, and kilovars
3	Potentiometer	Turbine gate position, gate limit and speed adjustment setting, and transformer tap position
2	Direct wire	Generator voltage and speed indicator
5	Direct wire	Synchroscope, incoming and receiving voltage, and frequency

16 points are for future expansion. Allocation of the supervisory points is given in Table II.

Telemetering

Continuously telemetered indicators with individual transmitters and receivers are provided for all important quantities to be metered. Intermittently telemetered indicators are provided for the less important quantities, with one transmitter and receiver provided for two or more quantities, with selection by supervisory control. The telemetering provided is shown in Table III.

It was recognized that fewer telemetered indicators could be used, since if abnormal conditions should develop, there is little that the operator at Ocoee 2 could do to correct the trouble, and the automatic protective devices would have to be relied upon to shut down the faulty equipment. It was felt, however, that the additional telemeters were justified because abnormal operation of the equipment may show up on the instruments just before shutdown, and the information obtained may be of value in locating the trouble.

Torque-balance-type telemeters are used for metering amperes, kilowatts, and kilovars. Individual instruments are provided for these quantities for the generator and for transformer 154- and 69-kv amperes. A common instrument is provided for transformer 154-kv kilowatts and kilovars, transformer 69-kv kilowatts and kilovars, 69-kv line amperes, and 69-kv line kilowatts and kilovars. Selection between kilowatts and kilovars and between lines can be made by supervisory control.

Potentiometer-type telemetering is used for turbine gate position, gate limit and speed adjustment setting, and main transformer tap position. It consists of small potentiometers, mechanically connected to the device whose position is being telemetered, and milliammeter receivers with appropriate scales. The potentiometers are connected to the Ocoee 3 250-volt control battery. To provide calibration of the receivers for change in battery voltage and line wire resistance, a rheostat is provided in one of the line wires of each receiver, and a supervisory point simultaneously connects the three receivers directly to the Ocoee 3 battery supply.

Generator voltmeter and synchroscope and associated voltmeters and frequency meters are operated directly over the line wires without telemetering transmitters, as is also the turbine speed indicator which is operated from a magneto-generator geared to the main unit shaft.

A recording voltmeter with milliammeter element is operated from a rectifier current transmitter with supervisory control selection of the voltage to be recorded. A station load recorder is operated from a thermoverter. A reservoir level recorder of the impulse type is provided with float-operated transmitter located at the dam. For this latter recorder, the line wires are run overhead on poles between the dam and Ocoee 3 powerhouse and thence through the underground cable to Ocoee 2.

Main Control Switchboards

The main control switchboards at Ocoee 3 are divided into three sections: the control and instrument board section, which is installed in one of the generator room walls and faces into the generator room; the relay board section, which is installed back-to-back to the control and instrument board; and the remote control board, which faces the relay board. Figure 4 shows a floor plan layout of the generator and switchboard rooms.

A complete set of controls and instruments is provided at Ocoee 3 for local control of the plant if desired for maintenance and when the supervisory control is out of service. A view of the control and instrument board is shown in Figure 5. The local controls are similar to the manual controls provided for other TVA plants except for several additional con-

Figure 2. Surge tank, valve house, penstock, powerhouse, and switchyard

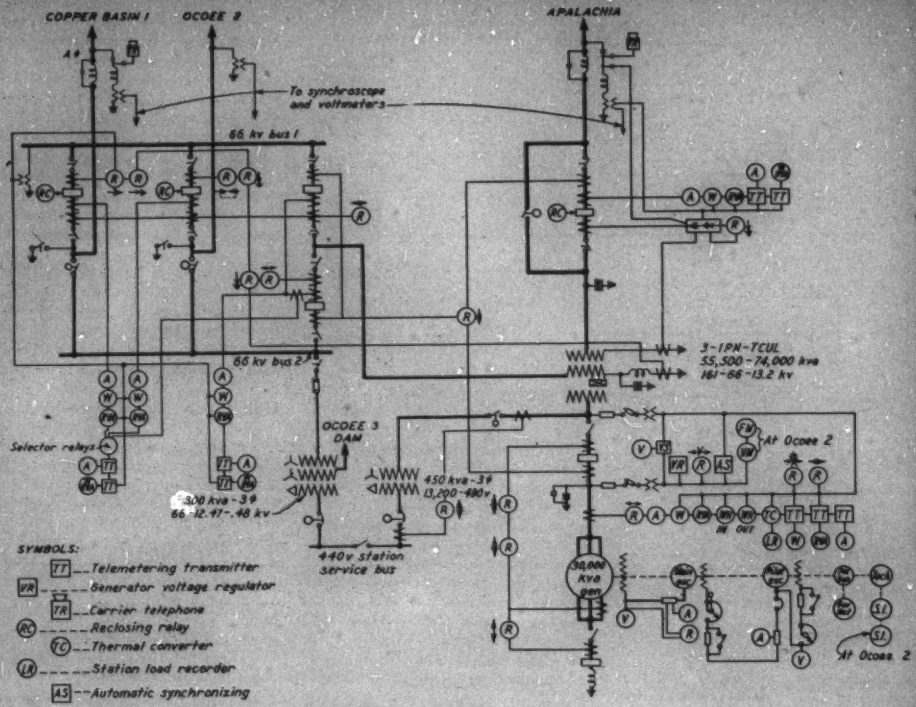

Figure 3. Single-line diagram of main connections and the principal metering and relaying

trol features required because of automatic and supervisory control operations. A switch is provided on each panel for transferring the controls on that panel to either local or supervisory control. On the generator panel a switch is provided to select either manual or automatic starting and synchronizing of the generating unit. A switch also is provided for selecting automatic synchronizing of the unit for manual starting when all auxiliaries are already in operation and it is not desired to go through the entire automatic starting sequence.

All of the main protective and automatic control relays for the generating unit, main transformer bank, and transmission lines are mounted on the relay board. Primary relays are of the withdrawal type with built-in test facilities. Differential relays are of the percentage-differential induction type. An automatic oscillograph is installed on the relay board, and facilities are provided to permit connecting the elements in the more important current and potential circuits for analysis of relay performance.

The supervisory control equipment, the telemetering transmitters, the battery charger controls, and the battery distribution equipment are located on the remote control board.

Dispatcher's Board at Ocoee 2

The dispatcher's board, consisting of a 2-panel completely enclosed cubicle, is installed at the left end of the Ocoee 2 main switchboard. A view of this board is shown in Figure 6. The recording voltmeter, generator-load recorder printing annunciator, and water-level recorder are mounted on one panel, and the indicating telemeter receivers and supervisory controls are mounted on the other panel. The supervisory controls and associated position-indicating lamps are grouped according to function, and mimic busses are provided so as to present a single-line diagram arrangement. The printing annunciator is of the impulse type and automatically prints on a paper chart all abnormal operations of the equipment at Ocoee 3 and also all opening and closing operations of the main circuit breakers.

Generating Unit and Governor

The generating unit consists of a 40,000-horsepower 200-rpm vertical-shaft Francis-type turbine direct-connected to a 30,000-kva 13.8-kv 0.9-power factor generator. The generator is totally enclosed, with Kingsbury-type thrust bearing located below the rotor and with direct-connected main and pilot exciters. The governor is of the actuator type with motor-driven governor head driven by a permanent magnet generator direct-connected to the main unit shaft.

The control and protective features of the main generating unit do not differ materially from those customarily provided for large manually operated units. The turbine guide bearing is lubricated normally by an a-c motor-driven oil pump with pressure switch control arranged to transfer on loss of pressure to an emergency battery-driven pump. An automatic control is provided for the wicket

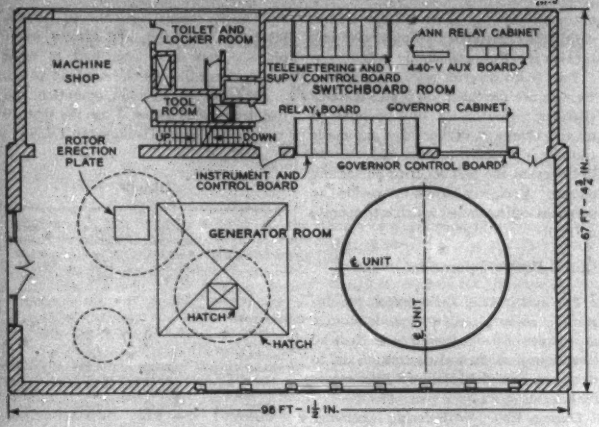

Figure 4. Main floor plan

gates to close and lock them in the closed position upon loss of governor oil pressure. The oil in the generator thrust bearing is self-circulating and no pumps are required. A float switch is provided to operate an annunciator for low thrust-bearing oil level. Temperature detectors are provided in the turbine guide bearing and generator thrust bearing for annunciation and for operation of a bearing temperature recorder mounted on the governor cabinet. An overspeed switch geared to the main shaft is arranged to energize the governor shut-down solenoid and operate an annunciator upon overspeed of the unit but does not close the butterfly valve. If the unit should run away, the operator at Ocoee 2 would be informed through the operation of the annunciator and the tachometer reading on the dispatcher's board and will close the butterfly valve by supervisory control.

The governor is of the conventional cabinet actuator type, with two motor-driven oil pumps and governing mechanism mounted on the sump tank. Both pumps are under pressure-switch control, and the control provides for the operation of one pump normally to maintain governor oil pressure. If this pump fails to maintain pressure, the second pump is started automatically. The governor manual controls, the penstock, scroll case, and cooling-water pressure gauges, the bearing "thermoverters," and the tachometer are mounted on the front of the governor cabinet.

The synchronizing and load-limit devices are motor-operated to permit operation of these devices by supervisory control and to permit automatic synchronizing by the automatic speed-matching and synchronizing relays on the main switchboard.

An automatic device is provided on the governor which, when the unit is started, allows the gates to open quickly to the speed-no-load position and then introduces a time delay to permit the governor flyballs to take control and the generator voltage to build up before the gates can be opened further for loading of the unit.

Automatically operated air brakes are provided to stop rotation of the unit after shutdown. Control is by an electrically operated pendulum timer which, after a time delay to allow the speed of the unit to drop to approximately 50 per cent of normal, applies the brakes intermittently until the unit is stopped. The control is interlocked through auxiliary switches to allow application of the brakes only if the wicket gates are completely closed and the generator breaker is open.

Generator Unit Protection

Protective equipment is provided to prevent starting of the unit if any of the following abnormal conditions exist:

1. Overspeed device contacts closed.
2. System voltage below normal.
3. Incorrect phase sequence.
4. Generator thermal relay contacts closed.
5. Exciter field rheostat not at normal voltage no-load position.
6. Main butterfly valve not fully open.
7. Generator neutral breaker not closed.
8. Main exciter field breaker not closed.
9. Lock-out relay not reset.

The following protective devices trip the generator breaker and shut down and

Figure 5. Generator room showing generator and main control and instrument board, with governor control board beyond

Figure 6. Dispatcher's board at left end of existing control board in Ocoee 2 plant

lock out the unit when abnormal conditions occur:

1. Generator differential and neutral overcurrent relays.
2. Generator thermal and phase overcurrent relays.
3. Generator a-c overvoltage relay.
4. Generator overvoltage relay for sustained overvoltage.

The following protective devices also trip and lock out the unit when abnormal conditions occur, but to prevent overspeeding, the generator breaker is not tripped until the wicket gates are closed to the no-load position.

1. Reverse-phase and unbalanced-phase current relays.
2. Field-failure relay.
3. Flow switches for low flow of turbine seal water, generator bearing water, and air cooling water.
4. Pressure switches for low governor oil pressure.
5. Float switch for low turbine-bearing oil level.
6. Temperature detectors for high turbine- and generator-bearing temperatures.
7. Incomplete starting sequence relay.

Station Service Supply

Normal auxiliary power is obtained from a 450-kva 3-phase 13.8/460-volt transformer connected to the main transformer delta bus through a motor-operated disconnecting switch. Emergency station service power is obtained from a 300-kva 3-winding 3-phase 69,000/12,450/460-volt transformer connected to the 69-kv transfer bus. The 12.45-kv winding supplies power to the dam over a 2.5-mile overhead line. Both transformers normally are kept energized, and automatic transfer control is provided to close the emergency supply 440-volt breaker if the normal supply fails.

Two 10-kw diverter-pole motor generator sets are provided for control-battery charging. One of the sets operates on floating charge at all times, and automatic transfer is provided to start the other set in the event the first set trips off for any reason. A selector switch is provided to permit selecting the set which is to operate normally.

Initial Power Operation

The operation of the reservoir for this plant is co-ordinated to provide storage in advance of floods, to fluctuate the pool elevations to aid in malaria control, and to store water on small stream flow increases for later use for power generation.

During the period from November 1942 to April 19, 1943, the sluice gates at the Ocoee 3 Dam were operated to regulate the downstream flow for power requirements at the Ocoee 1 and 2 plants and to meet the need of construction activities at the Ocoee 3 project. The gates were closed initially for the impounding of water to fill the reservoir on April 19, 1943. From this date on, the entire inflow, except that needed for the operation of the downstream Ocoee plants, was stored. The maximum reservoir elevation was reached on April 24, and the plant went into operation on April 30.

No attendants of any kind are stationed at the powerhouse or the dam. The necessary supervision and operation functions of the Ocoee 3 project are performed by the employees of the Ocoee 2 hydroelectric plant. A maintenance employee and an operating employee visit the plant two or three times a week to check batteries and lamps, test oil, inspect auxiliary equipment, clean switchboard panels, lubricate equipment, and inspect water plant. They stay from four to eight hours, depending on the work involved.

The cost of supervision, operation, and maintenance at Ocoee 3 for the first 20 months of operation is shown in Table IV.

Table IV

	First 8 Months 4/30 to 12/31 1943	Next 6 Months 1/1 to 6/30 1944	Next 6 Months 7/1 to 12/31 1944
Supervision			
Labor	$ 2,017	$ 1,410	$ 738
Material	612	384	168
Operation			
Labor	7,929	3,288	4,662
Material	2,153	612	528
Maintenance			
Labor	2,482	2,640	2,172
Material	536	804	636
Total cost	$15,728	$9,138	$8,904
Gross generation, kwhr	125,368,000	90,561,000	83,221,000
Cost per 1,000 kwhr	$0.125	$0.101	$0.107

The labor costs of supervision and operation are set up as 50 per cent of the salaries of the supervising, clerical, and operating employees. The material costs of supervision and operation and the entire cost of maintenance are charged 100 per cent to the plant.

Ocoee 3 is the first of the Tennessee Valley Authority's generating stations to be operated by supervisory control. Its excellent performance and low operation cost have encouraged an extension of this type of operation. Supervisory control is expected to be used for two other generating stations of larger capacity now under design and is being considered for a number of substations.

Signal and Noise Levels in Magnetic Tape Recording

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Synopsis: The primary object of the work described here was to determine what properties of the tape and associated magnetic elements are responsible for the noise and signal output levels of magnetic recordings and, if possible, to display in specific equations the pertinent relationships connecting noise and signal levels with the physical properties of the tape and polepieces. In the course of the study, methods appeared for decreasing the noise and increasing the useful signal reproduced from magnetic tape. These methods and some of the use that Bell Telephone Laboratories and Western Electric have made of them are mentioned in the discussion. While some of the work described in this paper has implications for more than one type of magnetic recording process, perpendicular recording on tape[1] is the actual subject matter dealt with. In every case discussed, the record medium was 0.050 inch wide and 0.0022 inch thick. Except where otherwise noted, a chrome-steel tape was used at a speed of 16 inches per second.

Noise Levels in Magnetic Tape Recording

Noise in Demagnetized Tape

In the experimental work on noise, the polepiece construction was as shown in Figure 1, where the active portion of each polepiece consisted of a sheet of soft magnetic material (for example permalloy) 0.0015 inch thick and 0.040 inch wide, held against the tape by a light spring tension with the narrow dimension parallel to the tape travel, the two polepieces exactly aligned with each other on opposite sides. When a piece of tape from which previous recordings have been erased by a demagnetizing process is passed between such polepieces, the signal picked up by the coils contains energy in a wide band of frequencies. This suggests that the noise may be caused by a large number of small magnetic irregularities in the tape. Therefore it is sensible to start by a quantitative consideration of the noise frequency spectrum that would be produced by such irregularities.

For concreteness, first suppose the tape is completely demagnetized except for one inclusion of magnetized material of dimensions small compared with the polepiece width (0.0015 inch). As the tape moves along, the flux passing into the polepieces must vary with time in some such way as that shown in Figure 2. The width of the flat top must be certainly less than the time required for the tape to travel one polepiece width (0.0015 inch); it may be substantially less than this. The portion of the tape that is so near the polepieces that an appreciable fraction of the flux of a magnetized inclusion gets into them will be called the region of influence of the polepieces in this paper. The curve of Figure 2 may be translated into a relative flux versus distance curve and plotted as in Figure 3; this curve $f(x)$ may be said to have the shape of the region of influence.* The course with time of the flux that links the windings is then given by

$$\Phi(t) = KMf[V(t-t_0)] \tag{1}$$

where V is tape speed, t_0 is the instant when the magnetized inclusion passes the center line of the polepieces, M is the magnetic moment of the inclusion, and K is a constant for the present considerations.

The voltage induced in the reproducing coils that surround the polepiece is

$$e(t) = KMnV \cdot 10^{-8} \frac{df}{dx} \tag{2}$$

where n is the number of turns on the coils. Figure 4 shows the shape of the voltage pulse $e(t)$ corresponding to the shape of the region of influence of Figure 3.

We are interested in the total power developed in the frequency range $\Delta\nu$ by the combined effects of N voltage pulses such as the above scattered at random throughout every time interval T. This problem is treated in Appendix I. The result is shown to be

$$P_N(\nu)d\nu = \frac{2(Kn\times 10^{-8})^2}{R} M^2 \left(\frac{N}{T}\right) S(\nu)^2 d\nu \tag{3}$$

where

$$S(\nu) = \int_{-\infty}^{+\infty} \frac{df}{dx} \sin \frac{2\pi\nu x}{V dx} \tag{4}$$

R is the impedance of the reproducing coil circuit, which is assumed to be a pure resistance independent of frequency. (Experimentally, this condition is met by connecting the reproducing coils to a high resistance.)

At this point it is possible to test whether the simple theory under investigation properly accounts for the observed shape of the noise frequency distribution. A complete test would involve computing $f(x)$ from the magnetic and geometric properties of the system and comparing the shape of the resulting $S(\nu)^2$ curve with noise measurements. It is not easy to compute $f(x)$ in more than an approximate manner. Therefore the reverse procedure has been employed. By trial and error an attempt has been made to draw an $f(x)$ curve that, employed in equation 3, leads to a noise frequency distribution that fits the observed facts. The result is shown in Figure 5, where the theoretically derived curve is superposed over the experimental noise measurements. The shape of the region of influence used in the derivation is shown in Figure 6. A study of the x-scale of this figure will show it to be reasonable for polepieces 0.0015 inch wide and tape 0.0022 inch thick.

The approximate agreement between theory and experiment that just has been established justifies some confidence in the validity of the methods and the theory under test. A somewhat more quantitative test may be obtained by comparing the noise frequency distribution and the signal frequency response characteristic. This method is developed in the following paragraphs.

In Appendix II it is shown that the power that is dissipated in the output load R when a sine wave signal of frequency ν is reproduced from the tape is

$$P_s(\nu) = \frac{1}{2} \frac{(Kn\times 10^{-8})^2}{R} (I_o a k)^2 V^2 T(\nu)^2 \tag{5}$$

where

$$T(\nu) = \int_{-\infty}^{+\infty} \frac{d}{dx} [f(x)g(x)] \sin \frac{2\pi\nu x}{V} dx \tag{6}$$

In these equations, I_o is the half-amplitude of the tape magnetization, measured when the tape is well away from the region of influence of the polepieces, while $g(x)$ is the factor by which the remanent magnetization of the free tape is enhanced

* Dependence of $f(x)$ on the depth of the inclusion in the 0.002-inch tape is taken account of only insofar as the $f(x)$ finally derived is thought of as a value averaged over the tape thickness.

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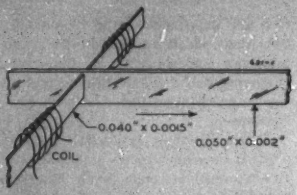


Figure 1. Dimensions of active portion of polepieces used in noise and signal level studies

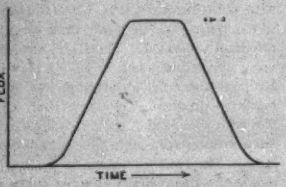


Figure 2. Time variation of flux in polepieces caused by a single small magnetized region in demagnetized tape

by the partial removal of the strong demagnetizing field brought about by the proximity of the reproducing polepieces. Letters a and h are the thickness of the tape and the polepiece height, respectively.

This expression for the reproduced power depends on frequency only through I_o^2 and $T(\nu)^2$. Moreover, I_o is practically independent of frequency if the same current is sent through the recording coils for all frequencies. For frequencies so low that the recording current remains substantially constant during the passage of an element of tape through the region of influence of the polepieces, it is obvious that this should be the case. But even for considerably higher frequencies, wherein the recording current changes appreciably while a tape element is near the polepieces, the amplitude of the recorded wave remains almost unchanged. This is because each tape element "remembers" the *highest* value of magnetizing field to which it is subjected, and not the last or even the average value. Actually, simple theory predicts a loss in I_o of two or three decibels at around 5,000 cycles, but this is opposed by a gain of roughly similar magnitude because of the decrease with decreasing wave length of the demagnetizing factor of perpendicular recording. Therefore we may take I_o to be independent of frequency and consider equation 5 to represent the over-all record-reproduce

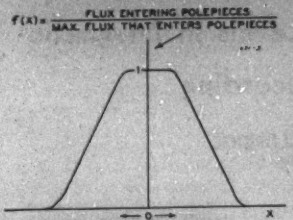

f(x) = FLUX ENTERING POLEPIECES / MAX. FLUX THAT ENTERS POLEPIECES
1
0
X
DISTANCE ALONG TAPE FROM MAGNETIZED REGION TO CENTER OF POLEPIECE

Figure 3. Qualitative shape of region of influence of polepieces

This curve is copied from one derived later and displayed in Figure 6. The sloping sides are actually curved, as indicated by the derivative curve of Figure 4. This curvature is not evident on such a small-scale figure

frequency response characteristic for constant recording current and a high impedance output circuit.

A comparison of equations 3 and 5 shows that

$$\frac{P_N(\nu)}{P_S(\nu)} = C \cdot \frac{S(\nu)^2}{T(\nu)^2} \qquad (7)$$

where C is a constant that is of no immediate interest. Moreover, $S(\nu)$ and $T(\nu)$ will be identical if $g(x)$ is a constant, that is, if the junction of the polepieces with the tape causes an inappreciable increase in the intensity of magnetization. Conversely, if the tape magnetization increases greatly because of the proximity of the polepieces, $g(x)$ will be a strongly peaked function similar to $f(x)$, and their product will be still more strongly peaked. In the first case, we should expect the noise and signal frequency characteristics to be the same; in the second case, the signal response should hold up to higher frequencies than the noise.

The conclusions of the preceding paragraph are valid only if the theory of noise on which equation 3 was derived is true, that is, that the noise is caused by many random magnetic irregularities less than 0.0015 inch in dimension. If the noise is attributable to any sort of mechanical vibration of the tape or polepieces, its frequency spectrum must be peaked at the vibration frequency or frequencies; the curve would bear little resemblance to that yielded by equation 3. If the noise is caused by many random irregularities in the tape which are *not* small in dimension compared to 0.0015 inch, the noise spectrum must be enhanced for wave lengths of the order of the irregularity dimensions. In such a case, the noise spectrum must have relatively less high frequency content than $S(\nu)$ and, therefore, less than $T(\nu)$, whether or not $g(x)$ is nearly constant.

On Figure 7 are replotted the noise measurements and the theoretical curve of Figure 5 together with signal output voltage measurements. The two sets of points have been shifted vertically along the logarithmic scale so that the low frequency 6-decibel-per-octave portions of the curves coincide. Figure 7 shows no concentration of noise at isolated frequencies, corresponding to vibration. Further, the high frequency content of the noise is definitely not lower than that of the signal response characteristic. In the light of the preceding discussions, this requires three conclusions:

1. The noise is produced by the passage between the polepieces of many randomly distributed magnetic irregularities.
2. The noise producing irregularities are smaller than 0.0015 inch in size.
3. $g(x)$ is not a strongly peaked function

While the data seem adequate to justify these conclusions, they do not explain how the noise characteristic can actually have *more* high frequency content than the response characteristic. However, the simple theory given here neglects a number of secondary effects and should not pretend to high accuracy in its predictions.

The conclusion that has been established is as important because of the noise producing mechanisms it proves negligible as for any positive contribution it may make to the theory of tape noise. For example, the noise cannot be caused by mechanical vibration of the tape or associated magnetic structures; it cannot be caused by variations in the magnetic properties of the tape because of mechanical eccentricities in the rolling mill; it cannot be caused by any kind of inclusion or grain size effect unless the dimensions of the irregularities are less than 0.0015 inch.

An obvious possible source of small magnetic irregularities in nominally demagnetized tape is found in the finite size of the magnetic domains that are believed to make up any permanent magnet. If a "demagnetized" tape is made up of many small magnetically saturated regions, oriented so as to cancel one another's field, there must be local imperfections in the cancellation process that result at any instant in the passage into the polepieces of a net flux different from zero. Statistical variations of this leakage flux along the tape must give rise to noise. In Appendix III a cal-

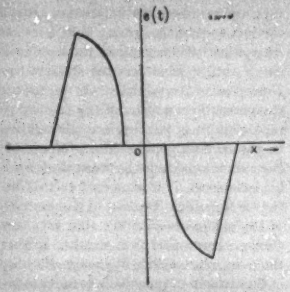
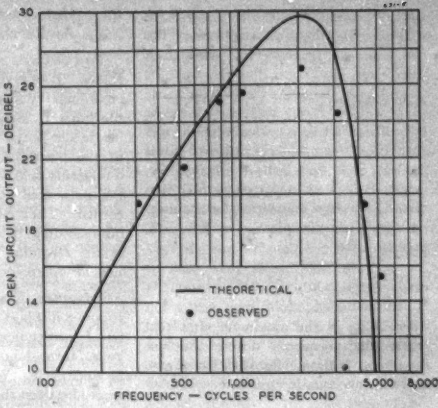


Figure 4. Voltage pulse corresponding to the region of influence shown in Figure 3

Figure 5. Comparison between observed noise spectrum of demagnetized tape and theoretical distribution based on region of influence of Figure 6

Tape speed = 16 inches per second. Polepiece width = 0.0015 inch



culation is carried out which leads to an expression for the open-circuit mean-square-noise voltage that should be measured if the tape consisted of saturated domains of volume v, with completely random directions of magnetization. The expression obtained is

$$E_N^2 = 3 \times 10^4 v \text{ volt}^2 \qquad (8)$$

Now, if the domain theory of the noise of demagnetized tape is an adequate one, equation 8 should predict a noise voltage considerably higher than that actually observed. This is because it is known that mutual interaction among the domains goes a long way toward cancelling out their resultant fields; the leakage flux must be only a fraction of that implied by random orientation, which was assumed in the derivation.

Measurements by various investigators [2,3] lead to values of v for most magnetic materials of the order of 10^{-9} to 10^{-8} centimeters.[3] For tape that is only 0.005 centimeter thick, there may be some reason to reject the higher figure, which corresponds to a linear dimension half as great as the tape thickness. Use of a value for v of 10^{-9} centimeters[3] in equation 8 leads to a noise voltage

$$E_N^2 \sim 3 \times 10^{-5} \text{ volt}^2$$

The experimentally measured value, for the conditions dealt with, is 2×10^{-11} volt.[3]

Obviously, the domain theory passes the first test of adequacy. From the derivation of Appendix III, it is clear that the observed noise can be accounted for even though the domains cancel all but 1/1,000th of one another's fields. It seems reasonable to conclude that the noise produced when demagnetized tape passes between the polepieces probably is caused by statistical variations in the flux leaving the tape owing to imperfect cancellation of the domain fields.

Noise in Saturated Tape

When tape from which previous signals have been erased by a saturation process is led through the polepieces, the noise produced in the output circuit is from 10 to 20 decibels higher than that of demagnetized tape, depending on the tape material, but it has the same frequency distribution. As in the case of demagnetized tape noise, this points to small magnetic irregularities as the likely source of the noise.

Since the tape is magnetized, nonmagnetic inclusions or variations in the coercive force or remanence would produce noise, where such irregularities would be ineffective in demagnetized tape. Steel tape is known to contain inclusions of carbon, whereas the coercive force and remanence, measured in the direction of tape magnetization, must vary with the orientation of the tiny crystals that make up the tape. Both these possible sources of noise have been investigated. Tape sections were etched and microphotographs made to reveal carbon particles and crystal boundaries. Measurements were made of the carbon particle sizes and numbers and of the crystal sizes. From such data, order of magnitude calculations of the resulting noise were made in a manner similar to the domain calculation of Appendix III. In both cases the predicted noise was far too low. Although there were probably some nonmagnetic inclusions in the tape that were not revealed by the etching processes used (austenite, for example), it seems unlikely that these inclusions could be numerous enough to account for the observed noise of magnetized tape.

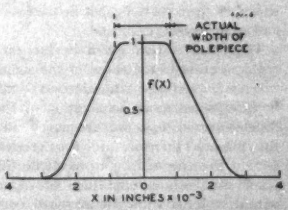


Figure 6. Shape of region of influence of polepieces assumed in deriving curve of Figure 5

As a result of these measurements and calculations, it has been concluded that the cause of noise in magnetized tape is probably rather similar to the cause of the lower noise of demagnetized tape. To account for the increased level, it is simply necessary to postulate that the process of saturating the tape and then decreasing its flux nearly to zero by its own demagnetizing field (see the section on signal levels) results in a greater degree of local disorder among the domains, whereby larger variations occur from point to point in the amount of flux leaving the tape surface.

Signal Levels in Magnetic Tape Recording

Equations 5 and 6 constitute a formal expression for the power output of a tape recording, but in greater detail than is needed for signal level considerations. For the present purposes, we may note that for an undistorted sine wave reproduction,

$$\Phi = \Phi_0 \sin 2\pi ft$$

where Φ is the flux linking the reproducing windings, and Φ_s is an amplitude. The rms induced (open-circuit) voltage is therefore

$$e = \sqrt{2}\pi n \Phi_s \times 10^{-8}$$

It will be convenient to deal with the flux that enters the polepieces rather than the fraction of it that links the coils. Recalling (as stated in Appendix III) that the ratio of these quantities, for the magnetic structures in question, is $2\frac{1}{2}$ to 1, we may write

$$e = \frac{\sqrt{2}\pi}{2.5} n \Phi_{REP} \times 10^{-8}$$

where Φ_{REP} is the maximum flux that enters the polepieces during the sine wave reproduction. Substitution of $n = 1{,}500$ in this equation gives

$$e = 2.6 \times 10^{-5} \Phi_{REP} \nu \qquad (9)$$

where e is in volts if Φ_{REP} is in maxwells and ν is in cycles per second.

The consideration given in the preceding section to the shape of the signal frequency response characteristic can be interpreted as an exploration of the dependence of Φ_{REP} on frequency and the reasons therefor. In the present section the aim will be to reconcile the observed absolute magnitude of signal output voltage with the physical constants of the tape-polepiece structure. It is both adequate and convenient to deal only with frequencies for which the wave length is so long compared with the region of influence of the polepieces that Φ_{REP} is independent of ν. Frequencies lying along the straight, 6-decibel-per-octave portion of the response curve of Figure 7 meet this requirement. Much of the data to be quoted will pertain to $\nu = 300$ cycles, for which equation 9 becomes

$$e_{300} = 8.0 \times 10^{-3} \Phi_{REP} \qquad (10)$$

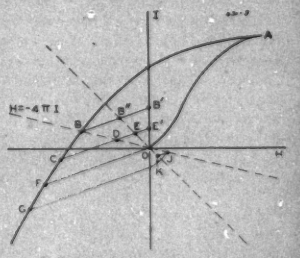
Before it is possible to obtain from equations 9 or 10 a figure for the output voltage that should be gotten from a magnetic tape recording, it is necessary to determine the value of Φ_{REP}. The development has implied clearly that the intensity of magnetization in an element of tape when it lies between the reproducing polepieces differs from the intensity in the same element when away from the influence of the polepieces, which in turn differs from the intensity that existed in the element when it lay between the recording polepieces. It is now necessary to examine in detail the hysteresis processes to which an element of tape is subjected during the erase-record-reproduce cycle.

Hysteresis Processes in the Erase-Record-Reproduce Cycle

Two methods of recording will be discussed. The first method erases previous recordings by bringing every element of the tape to magnetic saturation (perpendicular to the tape surface), and then, in the recording process, superposes a d-c biasing field on the fields produced in the polepieces by the signals being recorded. The second method erases previous recordings by demagnetizing the tape; in the recording process an a-c biasing field is superposed on the signal fields.

Saturation Erase; D-C Bias Record. Figure 8 displays the manner in which H and I (perpendicular to the tape surface) vary throughout the erase-record-reproduce cycle. When an element of tape passes between the erasing polepieces, its resulting magnetic state is represented by the point A. As the element of tape leaves the erasing polepieces, its intensity of magnetization drops. If there were no demagnetizing effect, the intensity of magnetization would take on the value given by the intersection of the hysteresis loop with the ordinate axis, that is, the remanence of the magnetic material. However, the tape is so thin compared with its other dimensions that the presence of perpendicular magnetization gives rise to a strong demagnetizing field that tends to diminish this magnetization. For the dimensions of the tape used, the demagnetizing factor is about 95 per cent of that which would be exhibited by an infinitely thin plane. For the purposes of this discussion, it is sufficiently accurate to take the demagnetizing factor as equal to that of the thin plane: 4π. Consequently, when the element of tape under consideration passes out of the influence of the erasing polepieces, its magnetization drops along the hysteresis curve until it intersects the straight line $H = -4\pi I$. Accordingly, B represents the magnetic condition of the element of tape while it is passing from the erasing to the recording polepieces. When this element of tape comes between the recording polepieces, it is subjected to two distinct influences. Because of the junction of the polepieces with the thin tape, the demagnetizing field is diminished so that the point representing the magnetic state of the element of tape tends to move along the line BB' towards higher values of magnetization. This increase in I either is augmented or retarded by the influence of the field that is momentarily produced by the currents in the recording and biasing coils. If these currents sum to zero, the magnetization in the element of tape moves up to a value B'', where the point B'' lies on another straight line that passes through the origin but which has a

Figure 8. Magnetic history of a tape element
Saturation erase; d-c bias record



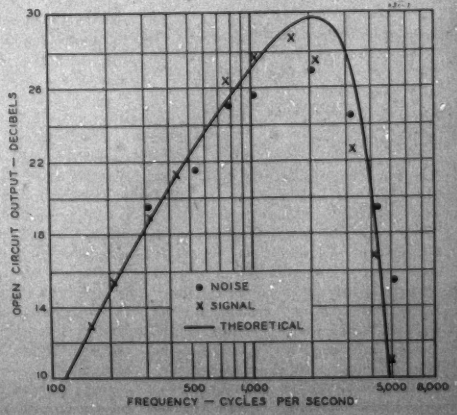


Figure 7. Comparison of noise and signal frequency characteristics

Theoretical curve and noise data copied from Figure 5

slope steeper than that of the line $H=-4\pi I$. The exact value of this slope depends upon the extent to which the demagnetizing field of the thin tape is removed by the junction of the polepieces. If the net field produced by the speech and biasing currents is positive at the instant in question, the point representing the magnetic state of the element will lie to the right of B''. If the field is negative, the representative point will lie to the left of B''. Now it is necessary to take account of an important property of most permanent magnet materials[4]; the hysteresis curve $BB''B'$ is nearly a straight line and is nearly reversible. This means that if the point representing the magnetic state of the element of tape while between the recording polepieces lies *anywhere* along the line BB', then the point which represents the magnetic state of that element after it leaves the recording polepieces will lie very close to B. (The representative point for an element of tape which is not in the vicinity of polepieces must always lie somewhere along the line $H=-4\pi I$.) This means that all values of recording fields that produce magnetic states in the tape represented by points lying between B and B' are nearly equivalent as far as the magnetization that they leave in the tape is concerned. It is evident, then, that when this method of recording is used, it is necessary to employ a negative biasing field so that all points representing the magnetic states of elements of tape while between the recording polepieces will lie somewhere along the hysteresis curve to the left of B. When this is done, the magnetic state of an element of tape while between the recording polepieces is represented by some such point at C. When that element of tape leaves the recording polepieces, its magnetization increases along the nearly straight line CE until the point D is reached. When the element of tape comes between the polepieces again for reproducing the magnetization moves up to the still higher value represented by the point E, as the demagnetizing field is diminished by the junction of the polepieces. Since over a limited range the curves whose intersections determine the positions of the points D and E are nearly straight, as is the hysteresis curve BC, the magnetization induced in the reproducing polepieces (at E) is linearly related to the recording current (at C).

The processes just described are shown in the curves of Figure 9, which have been plotted from tracings made on the screen of a cathode ray oscilloscope. The electrical circuit employed in these measurements was so arranged that the voltage supplied to the vertical plates of the oscilloscope was at every instant proportional to the flux density in the element of tape lying between the reproducing polepieces. (This was done by the use of low frequency sine wave recordings on the tape and an appropriate output integrating circuit); the voltage supplied to the horizontal plates was proportional to the recording current that had been used when this particular element was originally magnetized. (The fundamental of the reproduced signal, properly phase-adjusted, supplied this voltage.) In Figure 9, (a) corresponds to the case in which no biasing field was used on recording; in the case of (b), a small negative biasing field was used; in curve (c) a somewhat larger field, and so forth. The sine wave recording current was kept the same for all the curves. It is evident from these pictures that the phenomena described in the preceding paragraph have taken place. When the biasing field was small, as in (a) and (b), a large portion of the recording sine wave was nearly ineffective; when the biasing field became so large that the point representing the magnetic condition of the element of tape while between the recording polepieces always lay to the left of B (Figure 8), the reproduced signal was large and free from distortion, as in (c). When the biasing field became too great, the recording began to get into the overload region of the hysteresis curve, and as a result weak, distorted signals began to appear, as in (d) and (e). When the biasing field was positive, as in (b′) and (c′), the reproduced signals were weak and distorted, as was to be expected.

It has been seen that there is a sharp upper limit to the recording fields that can be employed, and that this limit is the field corresponding to the point B in Figure 8. There is also a lower limit. The lowest recording field which may be used without high distortion is the field corresponding to the point F. This is because the curves $BB''B'$, CDE, FO, and so forth begin to diverge markedly from straight lines if they are prolonged beyond the I axis. Consequently, the process GJK, which corresponds to a strong negative recording current, results in a reproduced negative intensity of magnetization I_K which is smaller than it should be if distortionless recording were to be done. This effect is shown in Figure 10. The measurements plotted on this figure were made on a rod of one of the materials from which our magnetic tape is made (vicalloy[5]), which had been heat treated so as to have approximately the same magnetic properties as the tape. (X-ray measurements on vicalloy tape show little preferred orientation of the crystals; hence the longitudinal properties of the rod and the perpendicular properties of the tape should be similar.) The rod was magnetized, demagnetized, and remagnetized in such a way as to

Figure 9. Oscillograms showing reproduced flux density as a function of recording current

Saturation erase; d-c bias record

a, b, c—Correspond to increasingly negative biasing fields

a, b′, c′—Correspond to increasingly positive biasing fields

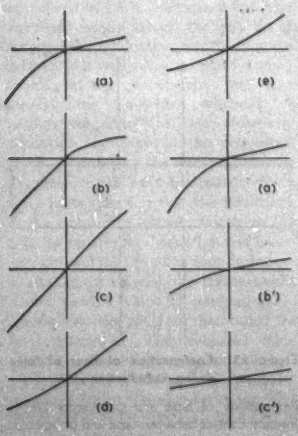
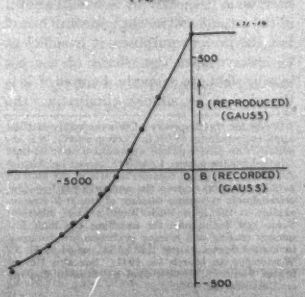


Figure 10. Plot of measurements on vicalloy rod when subjected to the hysteresis processes of the erase-record-reproduce cycle

Demagnetizing field assumed between record and reproduce $=-4\pi I$; at reproduce, $-(1/3)4\pi I$



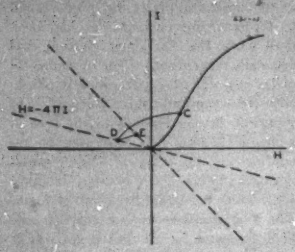


Figure 11. Magnetic history of a tape element

Demagnetization erase; no bias record

trace out curves of the type *ACDE* (Figure 8). For the relation between H and I characteristic of point E, a demagnetizing factor for the tape polepiece combination of amount $(1/3)4\pi$ was used. In later paragraphs it will be shown that a figure of $(1/2)4\pi$ might have been better, but the difference should not affect the conclusions drawn. From experimental determinations of the flux densities at various corresponding points C and E, the curve of Figure 10 was plotted, where the ordinate represents the flux density in the tape when in the reproducing position and the abscissa is proportional to the recording field which originally magnetized the tape. From Figure 10 it is evident that a linear relation between output flux and input field ceases to exist when the reproduced flux becomes negative.

Thus it is clear that this method of recording can employ only the recording currents that correspond to points on the line segment BF. The double amplitude of the maximum flux density that can be reproduced without high distortion is $B_{g''}$. This is only half the amplitude of the overload signal output. Therefore the conclusion: The maximum undistorted volume range of the magnetic tape for this type of recording is at least six decibels less than the maximum distorted range. This is an important practical result which always has been found to be true.

Demagnetization Erase; AC Bias Record. In the section on noise, it has been pointed out that demagnetized tape is 10 to 20 decibels less noisy than tape that has been saturated. Obviously it would be desirable to record on demagnetized tape. But if recording is done directly, without any biasing field, the reproduced signal is highly distorted. This is a natural consequence of the hysteresis cycle through which a tape element goes. In Figure 11, the letters C, D, and E have the same significance as in Figure 8, that is, they represent the state of the tape element while between the recording polepieces, while away from the polepieces, and while between the reproducing polepieces, respectively. Since the magnetization characteristic of a permanent magnet material is strongly curved near the origin, the reproduced intensity of magnetization at E could not be expected to have a linear relation to the magnetizing field at C. Such a linear relation can be achieved by the use of a d-c biasing field that causes recording to be done on the straight portion of the magnetization curve. However, the field required is so high that it restores the noise level practically to the value characteristic of saturated tape.

There is a method whereby the magnetization curve can be effectively straightened out and distortionless recordings thereby made on demagnetized tape. This result, which is achieved by the simple expedient of superposing on the recording fields a moderate field of supersonic frequency, is now well known in the art and will not be gone into here.* For the present purposes, it is sufficient to observe that the effects of the a-c biasing field are properly deduced if it is thought of as simply eliminating the curvature of the magnetization characteristic through the origin. Figure 12 shows the resulting hysteresis cycle through which an element of tape is taken. The curved path CD, which varies with the recorded signal strength is a feature of the hysteresis cycle that is not present in the other method of recording; it is conceivable that this might introduce nonlinearity in the relation between the reproduced magnetization and the recording flux density. In actual practice, however, this is found not to be the case; high quality recordings are produced by this method.

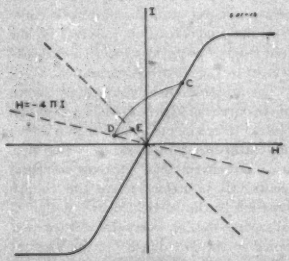


Figure 12. Magnetic history of a tape element

Demagnetization erase; a-c bias record

If the magnetization curve of Figure 12 were perfectly straight up to the saturation value of I, where it overloaded sharply, the double amplitude of the maximum distortionless reproduced flux density would be $2B_{g''}$ (see Figure 8). In such a case this method of recording would be capable of useful output levels six decibels higher than the method previously discussed. In practice the gradual nature of the overload reduces this gain to about four decibels.

Let us now return to the problem of calculating the level of the maximum useful signal that can be reproduced from the tape. Actually, let us deal with the saturation signal, from which we may deduce the maximum signal having comparatively low distortion.

We may start with equation 10, which now becomes

$$\frac{e_{300}}{\delta\Delta T} = 8.0 \times 10^{-3} \Phi_{g''} \qquad (11)$$

The problem now is to obtain a value for $\Phi_{g''}$, the maximum flux that enters the polepieces during the reproduction of an overload sine wave signal.

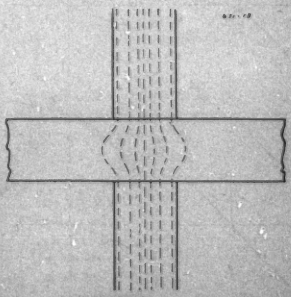


Figure 13. Configuration of lines of force during reproduction

Permeability of tape and polepieces $\gg 1$. Intimate contact between tape and polepieces

* Credit for the discovery of this recording method apparently belongs to W. L. Carlson and G. W. Carpenter, who filed a patent application on it in 1921 (United States patent 1,640,881, issued on August 30, 1927). The first commercial use of the method is believed to have been the audience-participation stereophonic recording display of the Bell System exhibit in the New York World's Fair, 1939–40. Some new techniques for handling the high frequency erasing and biasing problems are disclosed in United States patent 2,235,132, issued to D. E. Wooldridge on March 18, 1941. See also United States Patent 2,351,004, filed by Marvin Camras on December 22, 1941.

Evaluation of $\Phi_{B''}$

Figure 13 shows qualitatively the configuration of the lines of force in the vicinity of the reproducing polepieces. Although a large part of the flux leaks out of the side of a polepiece, through the air to the other polepiece, and back to the tape without linking the windings of the reproducing coils, this leakage is not shown on the drawing. Calculations of the reluctances of the leakage paths involved and search coil measurements agree in establishing that this leakage occurs well away from the pole tips, in a low reluctance portion of the magnetic circuit, and is properly taken account of by the factor of 0.4 that has been used in relating Φ_g and Φ_{REP}. All reluctances that are important in determining the amount of flux entering the polepieces are associated with the portion of the magnetic circuit shown on the figure.

The flux configuration depicted in Figure 13 is appropriate if the permeability of tape and polepieces is high and if intimate contact exists between them. In such a case, nearly all the flux enters the polepiece face, as shown.

The flux that passes into the polepieces may be determined from simple magnetic circuit considerations to be

$$\Phi = \frac{H_c a}{R} \tag{12}$$

where H_c is the value of H when $B=0$, which, for the pertinent hysteresis line $BB''B'$ (Figure 8), is simply the coercive force of the material; R is the reluctance of the complete magnetic circuit, including the tape, polepieces, and connecting yoke.

The reluctance of the circuit was measured directly. A single turn of fine wire was fitted snugly around the very tip of the polepiece lamination, and the voltage induced in it was measured when a small known 1,000-cycle current was sent through the 1,500-turn windings. A vicalloy tape that had been erased by saturation lay between the polepieces. In an obvious way the reluctance of the magnetic circuit was computed. Since there is no question that the reluctance of the circuit lies almost entirely in the pole tip tape region, both for this measurement and for the conditions during reproduction of a signal, this measurement should yield a value of reluctance approximately the same as that called for by equation 12. The measured value was 9.0 centimeter-gram-second units.

Substitution of $R=9.0$ in equation 12, together with the measured coercive force of 250 oersteds and the tape thickness of 0.0022 inch, gives $\Phi_{B'}=0.16$ maxwell. This value of $\Phi_{B''}$, when set into equation 11, predicts a 300-cycle-overload open-circuit reproduced signal of 1.3×10^{-3} volts. The value measured experimentally is 1.6×10^{-3} volts. The discrepancy lies within experimental limits.

Therefore it is possible to conclude that the reproduced signal levels are satisfactorily accounted for by the simple theory that has been given, wherein a detailed study of the hysteresis cycle through which a tape element travels has led to the conclusion that the maximum signal should be determined by the coercive force of the tape and the reluctance of the complete magnetic circuit.

If the theory is to be wholly satisfactory, it must meet the need of the analysis of the frequency characteristics of noise and signal, wherein it was pointed out that the similarity of the curves seemed to require that the magnetization of the tape element should not increase by a very large factor as it comes between the reproducing polepieces. The value of $\Phi_{B''}$ that has just been deduced, 0.16 maxwell, corresponds to a flux density of 180 gausses at the center of the polepieces, if $g(x)$ is *assumed* to be a constant and the flux therefore leaves the tape in accordance with the $f(x)$ shown in Figure 6. From the known relation between H and I, and therefore between B and I, given by the magnetic data that specify the hysteresis line $BB''B'$ of Figure 8 ($H_c=250$ oersteds, $B_{B'}=1{,}500$ gausses), this value of flux density can be computed to correspond to

$$4\pi I_{REP} = 400 \text{ gausses}^*$$

The value before the tape element comes between the polepieces is $4\pi I=250$ gausses. Therefore the assumption that $g(x)$ is constant leads to a result that is consistent with $g(x)$ varying by less than a factor of two, from $x=0$ to $x=\infty$ Replacement of the $f(x)$ used in this calculation by $f(x)\ g(x)$ for such a slowly varying $g(x)$ results in a trivial increase in the derived I_{REP} (about six per cent). It is clear that the correct figure for $4\pi I_{REP}$ at the center of the polepiece is not greatly higher than the value that has been calculated above, and that $g(x)$, as required by the frequency analysis, is such a slowly varying function that its replacement by a constant should produce only a slight change in the shape of the derived response characteristic.

* Thus $\frac{-H}{4\pi I}\sim 1/2$, under the assumptions used. That is, the demagnetizing factor in the presence of the polepieces is half as great as for free tape!

The analysis of signal levels is not complete without an inquiry into the reasonableness of the value of 9.0 centimeter-gram-second units that has been measured to be the reluctance of the magnetic circuit. The reluctance of the circuit is made up of two parts, that of the polepieces and connecting yoke, and the reluctance of the tape element itself. For the structures used, the polepiece-yoke reluctance is easily computed to have a value of about 0.2 centimeter-gram-second units. Use has been made already of the fact that this is a negligible part of the total reluctance. The reluctance of the tape element cannot be accurately computed without a detailed knowledge of the flux configuration, but an upper limit can be set by assuming no bending of the flux between the polepieces. When the appropriate permeability value (obtained from measurements of $B_{B'}$ and H_c for vicalloy) and dimensions are set in the obvious equations, a maximum reluctance of 2.2 centimeter-gram-second units is predicted for the tape. Thus the computations predict a reluctance for the magnetic circuit of no more than 2.4 centimeter-gram-second units, as contrasted with the value of 9.0 which was measured, and which properly accounts for the observed signal strength!

It seems likely that the high reluctance of the circuit is caused by a region of low permeability at the tip of each polepiece. This may be thought of as introducing an effective air gap between each pole tip and the tape. The measured reluctance corresponds to a width of 0.0005 inch for each of these air gaps. The existence of an effective air gap of this order of magnitude between the surfaces of soft magnetic materials when pressed together is a common phenomenon in magnetics.[6] The effective air gap is attributed primarily to the pole tips and not to the tape because the reluctance of the circuit was found to be affected but slightly when the tape was removed and the pole tips allowed to touch one another.

Practical Applications

Up to this point the method of procedure has been simply to subject some of the principal features of perpendicular magnetic tape recording to simple analysis in order to arrive at an improved understanding of the physical processes involved. This section is devoted to a discussion of some of the practical implications of the results of the preceding two sections.

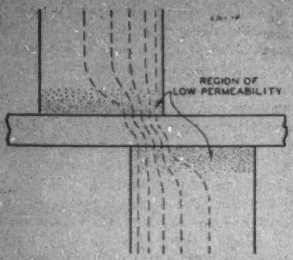


Figure 14. Action of wide offset polepieces

Reluctance of region of low permeability is decreased by increased cross section of the flux path. Region of influence is characteristic of the small overlap length and is not increased by wide polepieces

Increased Signal-to-Noise Level

If the conclusions reached in the first section are correct, a low noise level requires a tape material having a small magnetic domain size and/or a high degree of exactness in the mutual cancellation of the domain fields. The present state of magnetic domain theory does not permit the correlation of tape noise with any measurable magnetic properties. Empirical experiments on various kinds of tape have revealed no such correlation. The only useful generalization that can be drawn about tape noise is that demagnetized tape is always quieter than tape that has been saturated.

From the second section of this paper, a high signal level should be produced by a tape having a high coercive force. This principle guided Bell Telephone Laboratories in the development of vicalloy tape, which has a coercive force of 200 to 250, compared with the value of 40 or 50 characteristic of the chrome steel alloy formerly used. The signal output level is higher than that of the chrome steel tape, but the noise level is not enhanced. When recording is done on demagnetized vicalloy tape by the method that employs a supersonic field superposed on the recording field to straighten out the magnetization characteristic, a volume range (to overload) of 55 decibels is obtained. This signal-to-noise ratio is obtained in a system equalized from 100 to 8,000 cycles, at a tape speed of 16 inches per second. The equalization is done in the output circuit only. Under these circumstances the volume range is practically independent of frequency.*

* This is a consequence of the similarity between the noise and signal frequency characteristics.

The useful volume range depends on the harmonic content that can be tolerated but is several decibels fewer than 55.

This combination of vicalloy tape and the superposed high frequency method of recording first was used commercially in the audience-participation stereophonic recording display of the Bell System exhibit in the New York World's Fair, 1939–40.

Simplified and Improved Polepiece Structure

When it was discovered that the output signal level was being limited largely by a region of high reluctance in the tips of the polepieces, a search was instigated for polepiece material that would exhibit lower tip reluctance than the molybdenum permalloy in use. The search succeeded in turning up a few other materials as good as the molybdenum permalloy but none better. The resultant directing of attention to other ways of decreasing this reluctance led to the idea of replacing the thin exactly aligned polepiece laminations by wide offset polepieces such as those pictured in Figure 14. The hope was that the region of influence of the polepieces would be controlled by the small overlap so that high frequency sensitivity would not be lost, but that the flux would be able to spread out in the region of low permeability, thus decreasing the reluctance and increasing the output signal level. On Figure 15 are replotted from Figure 7 the output signals obtained from the usual record-reproduce unit, in which the magnetic part of the pole faces consists of a 0.0015 inch by 0.040 inch lamination. In addition are plotted measurements on a unit in which the polepieces consist of molybdenum permalloy rod 0.041 inch by 0.040 inch, the leading edge of one polepiece being exactly opposite the following edge of the other (no overlap in Figure 14). The vertical difference between the two curves is adjusted for the measured difference in flux loss from pole tips to coils for the two units. The two curves correspond to recorded levels the same distance below saturation. Figure 15 shows a general increase in the output level that may be attributed to the expected decrease in pole tip reluctance. The shape of the high frequency portion of the curve is somewhat different for the new unit, but there is no evidence of an increase in the effective polepiece width. The upward bulge in the response of the new unit at low frequency is caused by a longitudinal component of magnetization, which, for the polepiece dimensions used, has a maximum at 200 cycles. This is all to the good, of course, since it reduces the amount of equalization needed. The position of this bulge is controlled by the width of the polepieces. This is the principal reason for the use of pieces 0.041 inch wide. The over-all signal level and moderate-to-high frequency response are just as high for 0.020-inch pieces, for example.

The wide, offset polepieces are also more efficient on recording, about eight decibels fewer ampere turns being required to saturate the tape than with the old unit. Furthermore, the 0.041-inch tip is sturdy and self-supporting. Its use permits a much simpler and cheaper record-reproduce unit design than that associated with the thin laminations, which had to be incorporated in a supporting structure of bakelite and brass and provided with a fairly complicated framework containing guides and yokes. The mechanics of the thick polepiece structure also permit a coil design that recovers practically all of the reproduced

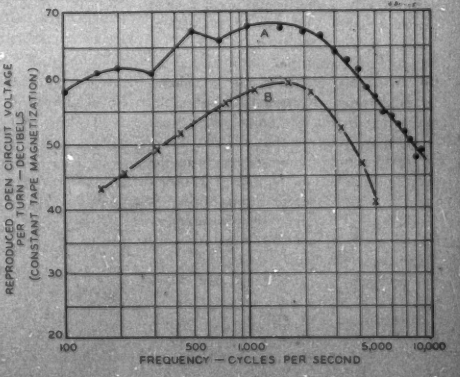


Figure 15. Comparison of output efficiencies of narrow aligned polepieces and wide offset polepieces

Curve *A*—Polepiece dimensions, 0.041 inch by 0.040 inch
Curve *B*—Polepiece dimensions, 0.0015 inch by 0.040 inch
Tape speed = 16 inches per second

flux that in the older structures leaked out of the polepieces without linking the windings. This adds another eight decibels to the relative efficiency of the new unit. As a result of all these gains, the new unit has an over-all record-reproduce transfer loss twenty-six decibels fewer than that of the old unit at 1,000 cycles. The complete comparison of the efficiencies of the two units is given in Figure 16.

Figure 17 shows the record-reproduce unit used in the Western Electric Mirrophone. The unit contains two polepiece-coil structures, one for erasing, the other for recording and reproducing.

Summary

In the first section of this paper, it was shown that the shape of the noise frequency distribution curve of both magnetized and demagnetized tape can be semi-quantitatively accounted for if it is assumed that the noise is caused by many random magnetic irregularities in the tape, of average dimension smaller than 0.0015 inch. An incidental result of the treatment was a derivation of the shape of the signal frequency response characteristic and an explanation of its similarity to the noise frequency distribution. Various possible sources of noise were examined. The only source found to be qualitatively and quantitatively acceptable consisted of statistical variations in the net flux entering the polepieces because of the finite size of the magnetic domains of the tape material.

In the section on signal levels, detailed consideration was given to the hysteresis processes through which an element of tape travels in the erase-record-reproduce cycle. Both the saturation erase d-c bias record and the demagnetization erase a-c bias record systems were considered. It was shown that the latter system not only is less noisy than the former, but also is capable of somewhat higher level high quality recordings. The magnitude of the overload signal was predicted in terms of the coercive force of the tape material and the reluctance of the magnetic circuit. The signal level prediction was shown to be in satisfactory agreement with experiment. The measured reluctance of the magnetic circuit was found to be so high that it required the existence of an effective air gap of about 0.0005 inch between each pole tip and the tape surface.

In the last section of the paper, it was shown how the search for a tape material having the characteristics that the theory indicated should give a high signal output, resulted in the development by the Bell Telephone Laboratories magnetic and metallurgical groups of a vicalloy tape having a markedly higher signal-to-noise ratio than had previously been obtainable. Attempts to diminish the pole tip reluctance that had been concluded to be a limiting factor in output signal strength were shown to have led to the development of a new type of record-reproduce unit with an improved frequency response, increased efficiency, and greatly simplified design. By a combination of vicalloy tape, the superposed high frequency method of recording, and the new unit design, high quality recordings equalized from 100 to 8,000 cycles with a useful volume range of more than 50 decibels can be made. A tape speed of only 16 inches per second is required, and the erase-record-reproduce unit combines simplicity of construction with low transfer loss.

Figure 17. Illustration of erase-record-reproduce unit used in Western Electric Mirrophone

Tape guides and dust cover removed

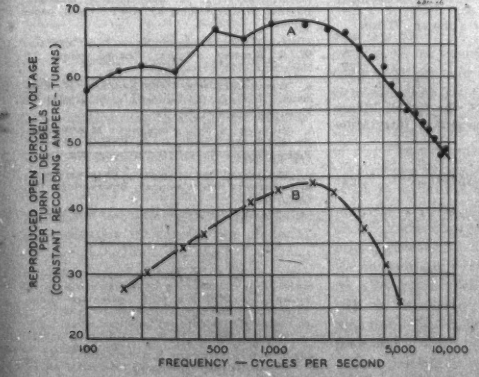


Figure 16. Comparison of over-all record-reproduce efficiencies of new (A) and old (B) units

Recording ampere turns the same for all measurements. Tape speed = 16 inches per second

Appendix I. Frequency Distribution of Noise Power Caused by Random Small-Voltage Pulses

The Fourier expansion of the $e(t)$ of equation 2 over a time interval T which includes the pulse in question is

$$e(t) = \sum_{m=1}^{\infty} B_m \sin\left(\frac{2\pi m t}{T} + \Phi_m\right) \qquad (13)$$

where

$$B_m = 2KMn \times 10^{-8}.$$

$$\frac{1}{T}\int_{-\infty}^{+\infty} \frac{df}{dx} \sin\frac{2\pi m x}{VT}\, dx \qquad (14)$$

In equation 13 the phase Φ_m depends on the position of the pulse in the time interval chosen for the expansion. Extension of the limits of integration to $\pm\infty$ is permissible since the integral is zero outside of the small interval occupied by the pulse.

The power developed in the frequency range $\Delta\nu$ by the combined effects of N voltage pulses, such as the above scattered at random throughout every time interval T (large compared with the pulse duration), is

$$P_m(\nu)\Delta\nu = \frac{1}{R}\sum_{m_1}^{m_2} E_m^2 \qquad (15)$$

where the reproducing coil circuit is assumed to have a resistance R for all frequencies, and the range $m_2 - m_1$ is related to $\Delta\nu$ through the equation

$$\frac{m_2 - m_1}{T} = \Delta\nu \qquad (16)$$

E_m^2 is the mean square noise voltage at frequency m/T and is

$$E_m^2 = 1/2NB_m^2 \qquad (17)$$

In equation 17 the 1/2 is caused by the usual relation between average power and voltage amplitude. NB_m^2 is the square of the amplitude of the noise voltage of frequency m/T, caused by N voltage pulses of identical size and shape scattered at random throughout the interval. (In the case of random phases of the elementary pulses, the squares of the amplitude add directly.) Combinations of equations 14, 15, 16, and 17 give, for the noise power in the range $d\nu$ at frequency ν,

$$P_n(\nu)d\nu = \frac{2(Kn\times 10^{-8})^2}{R} M^2\left(\frac{N}{T}\right) S(\nu)^2 d\nu \quad (18)$$

where

$$S(\nu) = \int_{-\infty}^{+\infty} \frac{df}{dx} \sin\frac{2\pi\nu x}{V} dx \quad (19)$$

Appendix II. Frequency Response Characteristic of Tape Recording

The problem to be considered is the following: For a given sine wave intensity of magnetization on the tape before it passes between the reproducing polepieces, how does the mean square reproduced signal power depend upon frequency?

At any instant the flux that enters the polepieces from an element of tape of length dx a distance x from the center line of the polepieces is

$$d\Phi = Kd\,Mf(x) \quad (20)$$

where dM represents the magnetic moment of the specified element of tape and the other quantities have the same meaning as in equation 1. For dM we may write

$$dM = ahI(x)dx \quad (21)$$

where a = tape thickness (0.0022 inch), h = polepiece height (0.040 inch), and $I(x)$ = intensity of magnetization of the tape a distance x from the center line of the polepieces. $I(x)$, in turn, may be expressed as

$$I(x) = g(x)I_0 \sin\frac{2\pi\nu}{V}(x - Vt) \quad (22)$$

where $I_0 \sin\frac{2\pi\nu}{V}(x-Vt)$ describes the variation with x and t of the magnetization that would exist if the reproducing polepieces were removed from the tape, while $g(x)$ is the factor by which the remanent magnetization of the free tape is multiplied by the partial removal of the strong demagnetizing field brought about by the proximity of the reproducing polepieces.*

* The hysteresis processes involved are discussed in the section on signal levels.

Equations 20, 21, and 22 give

$$\Phi = KahI_0 \int_{-\infty}^{+\infty} f(x)g(x) \sin\frac{2\pi\nu}{V}(x - Vt)dx \quad (23)$$

Employment of the conditions $f(+x)\,g(+x) = f(-x)\,g(-x)$ and $f(\infty)\,g(\infty) = 0$ permits simplification to

$$\Phi = \frac{V}{2\pi\nu} KahI_0 \sin 2\pi\nu T(\nu) \quad (24)$$

where

$$T(\nu) = \int_{-\infty}^{+\infty} \frac{d}{dx}[f(x)g(x)] \sin\frac{2\pi\nu x}{V} dx \quad (25)$$

The reproduced signal power is

$$P_s(\nu) = \frac{1}{2}\frac{\left(10^{-8}n\frac{d\Phi}{dt}\right)^2_{\max}}{R}$$

or

$$P_s(\nu) = \frac{1}{2}\frac{(Kn\times 10^{-8})^2}{R}(I_0 ah)^2 V^2 T(\nu)^2 \quad (26)$$

Appendix III. Tape Noise Caused by Saturated Domains of Random Orientation

The calculation must start with an evaluation of the constant K, of equation 18. K is the amount of flux that links the windings of the reproducing coils because of an element of unit magnetic moment lying directly between the polepieces. For the magnetic structures used in these tests, only about 40 per cent of the flux that entered the poletips succeeded in linking the windings. The exact value of the flux that enters the polepieces because of a magnetized region between them depends in a complicated way on the depth of the region in the tape and on the magnetic and geometric properties of the tape-polepiece structure. However, the correct answer can be shown to lie within a factor of three or four of $4\pi\frac{M}{a}$. This is accurate enough for the purpose at hand. Thus

$$K \sim \frac{4}{2.5}\frac{\pi}{a} \sim \frac{4}{a} \quad (27)$$

For evaluating $S(\nu)^2$, the $f(x)$ of Figure 6 may be used. A graphical integration gives

$$\int_0^{5,000\text{ cycles}} S(\nu)^2 d\nu = 5{,}500\text{ sec}^{-1} \quad (28)$$

Therefore, from equations 18, 27, and 28,

$$E_N^2 = R\int_0^{5,000\text{ cycles}} P_N(\nu)d\nu$$

$$= 1.76\times 10^{-11} n^2 \frac{M^2}{a^3}\left(\frac{N}{T}\right) \quad (29)$$

where E_N^2 is the mean square open-circuit noise voltage, measured in a circuit covering the frequency range 0–5,000 cycles, and M, a, and T are in centimeter-gram-second units. For the reproducing coils used, n = 1,500 turns, whereas the tape thickness was about 0.005 centimeter. Therefore equation 29 becomes

$$E_N^2 = 1.58 M^2\left(\frac{N}{T}\right)\text{ volt}^2 \quad (30)$$

Both M and N/T depend on the domain size. If we consider it to have a volume v,

$$M = vI_{SAT}$$

where I_{SAT} is the saturation intensity of magnetization of the tape. For the materials used, $B_{SAT}\sim 15{,}000$ gausses, or $I_{SAT}\sim 1{,}000$ centimeter-gram-second units.

$$M \sim v\times 1{,}000 \quad (31)$$

For the number of domains per second that pass by the polepieces,

$$\left(\frac{N}{T}\right) = \frac{Vha}{v}$$

Substitution of the values V = 16 inches per second, h = 0.040 inch, a = 0.002 inch, gives

$$\left(\frac{N}{T}\right) = \frac{0.021\text{ cm}^2\text{ sec}^{-1}}{v} \quad (32)$$

Equations 30, 31, and 32 give

$$E_N^2 = 3.3\times 10^4 v\text{ volt}^2 \quad (33)$$

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The Mho Distance Relay

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THE NEED for more adequate discrimination by means of distance relays, between fault conditions and power swings has been heightened in recent years by the construction of longer transmission lines and by the transmission of larger amounts of energy over existing lines.

Several recent papers[1,2,3] have described the inadequacy of the impedance- and reactance-type directional distance relays to fulfill this need without the addition of auxiliary operating units. Auxiliary units always introduce additional sources of trouble, increase the need for maintenance, and make the maintenance more difficult. R. E. Cordray and A. R. van C. Warrington have described the use of a relay which measures a constant component of admittance for providing this discrimination, in addition to providing correct directional action and accurate distance measurement, all in one unit.[4] This characteristic has been named a mho characteristic.

Figure 2, which has been taken from their paper, illustrates how a relay at A, with a mho characteristic set to protect 90 per cent of the line to B, will operate over a smaller band of power swing conditions than the impedance or reactance-type relays. The line AB is the locus of impedance seen by the relay for metallic faults along the line. The mho distance relay operates for impedances within its circle. The impedance-type relay operates for impedances which lie within its circle of constant impedance and which are above and to the right of the straight-line characteristic of the directional element. The reactance-type relay operates for impedances which lie below its constant reactance locus and which are within the circular characteristic of the starting unit. It has been shown that a relay with the mho characteristic will provide instantaneous tripping during a power swing only if the electrical center of the system is within the section of the line protected by the relay and only if the voltages at the ends of the section become approximately 90 degrees out of phase. Such a condition usually indicates loss of synchronism, and it is usually desirable to sever the system at its electrical center.

It is the purpose of this paper to describe a 3-step distance relay operating on the mho principle. It has three independent units, each capable of providing a complete mho characteristic, thus approaching the ultimate in relaying simplicity—one contact in the trip circuit. Three mho distance relays (type GCY), with an auxiliary timing relay, provide 3-step distance phase protection to one terminal of 3-phase line. This relay also can be used as part of a distance pilot carrier-current relaying terminal.

Every high-speed distance relay has a tendency to trip on faults beyond its ohmic setting when the fault current has a large d-c offset. The induction cylinder-type mho relay has reduced this transient overreach to a few per cent, even for highly lagging transmission line circuits.

Another unique characteristic of the mho unit is its "memory action," which provides a strong polarizing flux for even a zero voltage fault. This condition causes the relay to operate fastest for nearby faults.

Arrangement

The general arrangement is shown in Figure 3, and the ohmic characteristics in Figure 4A. Each mho distance relay has three units providing 3-step directional distance protection for faults between two phases of a 3-phase line.

The first or instantaneous tripping zone is provided by the M_1 unit, which is usually set to operate for faults within the first 90 per cent of the protected section AB. The M_1 unit operates through contacts with a slight time delay to clear faults in the neighborhood of the next bus at B. The conventional third zone, providing time delay backup for faults beyond B, is provided by the offset mho unit, OM_3. The offset, resulting in an ohmic characteristic which encircles the origin, provides a strong steady torque for faults in the vicinity of the relay bus. As a by-product, it provides time delay backup for nearby faults in the reverse direction. It can be used with no offset if desired.

It is possible to reverse the polarity of the OM_3 unit to obtain the reversed OM_3 connection shown in Figure 4B. This provides time delay backup for faults between A and the bus behind it at D. The merits of the reversed OM_3 connection are discussed in a companion paper.[5]

One mho distance relay of drawout construction which affords ease of maintenance and testing is illustrated in Figure 1. The relay occupies approximately 6 by 20 inches of panel space.

Three mho distance relays combine with a common timing relay to give directional distance protection from one end of a 3-phase line. An elementary diagram for the relays at one terminal is shown in Figure 5. For clarity, the d-c connections to two of the mho distance relays are indicated by light lines because they parallel the connections of the third relay.

Figure 1. The mho distance relay

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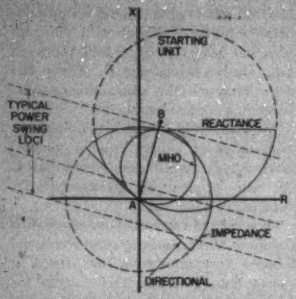


Figure 2. Impedance diagram illustrating tripping zones for impedance, reactance, and mho-type directional distance relays at *A* set to protect 90 per cent of the line *AB*

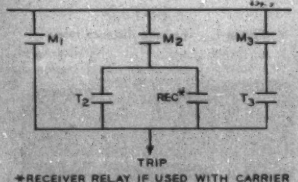


Figure 3. Fundamental trip circuit

The seal-in unit in each mho distance relay gives a target indication to show which phases are affected, while the targets mounted in the timing relay indicate which distance zone has operated.

Construction of the Mho Units

The mechanical construction of the mho unit is shown in Figure 6. Four laminated poles encircle a stationary core or inner stator with a small annular air gap between. Within the annular gap there turns an aluminum induction cylinder supporting a lightweight moving contact structure. The contacts are fine silver cylinders at right angles to provide the ideal point contact and are protected from excessive pressures by means of a clutch. This clutch is adjusted by means of a helical spring on the rotating shaft. The lead-in spiral for the contacts acts as a light control spring to give the contacts a positive position when the relay is de-energized. A lower jewel bearing with a highly polished pivot at the bottom of the shaft and a highly polished guide pin engaging a phosphor bronze bushing in the top of the shaft reduce friction to an almost imperceptible amount.

The arrangement of the coils on a unit which operates for faults between phases 1 and 2 is shown schematically in Figure 7A. The unit is polarized by the same potential that provides the restraining torque and derives its operating torque from double current windings, providing flux proportional to the difference of the currents in the two phases involved. This condition provides the same reach for 3-phase, phase-to-phase, or double phase-to-ground faults.

The two side poles carry the polarizing windings, which are tuned by the capacitor C_2 to have a slightly leading current. This condition causes the natural frequency of the polarizing circuit to be very close to 60 cycles. Therefore, when the terminal voltage drops to almost zero during bus faults, the polarizing flux continues for a period long enough to cause most rapid operation of the unit. See Figures 13, 14, and 15.

Figure 8 illustrates a cathode-ray oscilloscope screen with a recurrent sweep showing the current in the polarizing coils before and during a zero-voltage fault. The accuracy required of the M_1 unit during transient conditions makes the tuning of this circuit critical, so that the tuning reactor X_1 is used in this unit only. In the past, memory action has been incorporated into units which had a primarily directional function. For this purpose, phase resonance[4] was used and proved satisfactory, but to obtain accurate distance measurement also, it is necessary to tune to period resonance. Tuning a circuit for phase resonance produces current at unity power factor, which is the condition generally considered as resonance. Tuning for period resonance produces a circuit whose natural frequency is equal to the frequency of the applied voltage. When resistance is present, there is a difference between these two types of tuning.

Returning to Figure 7A, the restraining flux in the rear pole is supplied by two coils on the rear of the magnetic structure. The size of the ohmic characteristic is adjusted by means of taps on an auto-transformer. The resistor R_1 is provided for a factory adjustment of the maximum restraint setting. The capacitor C_1 provides a certain amount of memory action to the restraining circuit of the M_1 unit to aid in preventing false operation of the unit during transient conditions at the inception of a fault, either caused by unsymmetrical currents or the result of mechanical rebound caused by spring in the lightweight rotating structure upon a sudden loss of restraining torque.

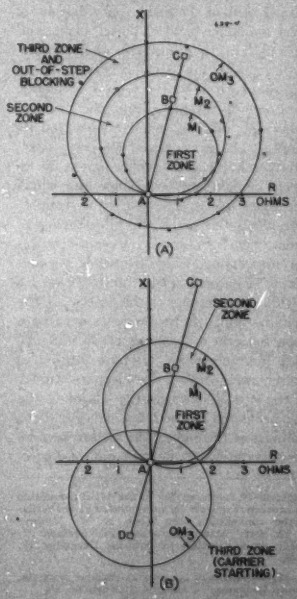
The current coils for providing operating flux to the front pole are wound on top of flux shifting windings on the two front legs of the magnetic structure.

With the accurate tuning of the polarizing circuit of the M_1 unit, no phase shift of the operating flux is necessary to obtain maximum operating torque at 75 degrees lag, because the circuit constants are such that tuning for maximum torque at 75 degrees and natural frequency at 60 cycles occur at the same point. Therefore the flux shifting coils are open-circuited for the 75-degree setting. Use is made of the flux shifting coils in order to obtain two other values of the angle of maximum torque, 60 degrees and 45 degrees. Using capacitive circuits to complete the circuit in the M_1 unit aids in reducing transient operating torques caused by d-c components in the current waves. The angle of maximum torque of the M_1 unit is selected by means of leads on a connection block.

The connections of Figure 7A for the M_3 unit are schematic in that the circuit of the flux shifting coils is completed permanently through R_3 instead of being brought out to a connection block. Ad-

Figure 4

A. Typical setting of mho distance relay for conventional 3-step protection
B. Typical setting of mho distance relay using the reversed OM_3 connection



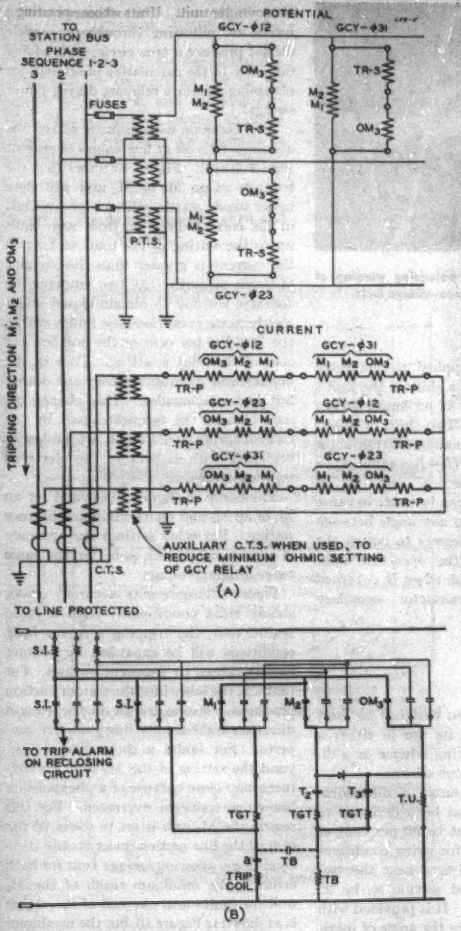


Figure 5. Elementary diagram of connections for one 3-phase terminal

A. A-c circuits
B. D-c circuits

M_1 = mho unit, first zone
M_2 = mho unit, second zone
OM_3 = offset mho unit, third zone
TR-P = transactor primary
TR-S = transactor secondary
S.I. = seal-in unit
T.U. = timing relay operating circuit
T_2 = zone 2 contact of *T.U.*
T_3 = zone 3 contact of *T.U.*
TGT = target
TB = relay for blocking instantaneous reclosing after time delay trip. Omit *TB* if this feature is not required, and connect lower terminals of all three targets
a = auxiliary switch closed when breaker is closed

A. A single mho unit

B. Exploded view of mho unit

Figure 6

justment of the R_2 will provide a continuous range from 60 degrees to 75 degrees for the angle of maximum torque.

The restraining torque of the M_1 and M_2 units is given by the expression $K_1E_{pol}E_{rest}$, where K_1 includes the sine of the angle between the two fluxes and the restraint transformer tap setting. The operating torque expression is $K_2E_{pol}I\cos(\phi-\theta)$, where θ is the phase angle of the relay characteristic, depending upon the phase angle of the polarizing circuit and the phase shift of the operating flux by the flux shifting circuit, and ϕ is the phase angle of the fault current ($I=I_1-I_2$). Therefore the relay torques are balanced when $E_{pol}\,(I\cos(\phi-\theta)-(K_1/K_2)E_{rest})=0$. E_{pol} can be cancelled out of the preceding equation because it is not zero, even for zero voltage faults, because of memory action, leaving

$$\frac{E_{rest}}{I\cos(\phi-\theta)}=\frac{K_2}{K_1}$$

At the angle of maximum torque, $\phi=\theta$ and $E_{rest}/I=Z=K_1/K_2$.

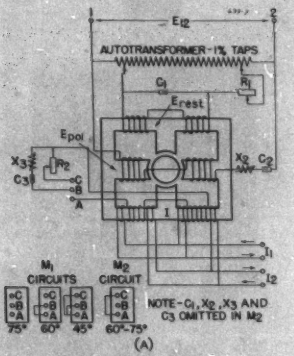
With the closest manufacturing tolerances attainable, it is impossible to eliminate very minor mechanical, and consequently magnetic, dissymmetries from the unit. These introduce spurious torques proportional to the current squared which become strong enough under short-circuit conditions of high current and low voltage to overcome the torques produced by interaction with the polarizing flux.

These torques are reduced to negligible magnitudes by two means. The current coils are connected in parallel in order that the induced voltages in each of a pair of windings will be as nearly equal as possible, thereby producing equal fluxes. Any further adjustment that is

necessary is made by a slight shift in the position of the inner stator by means of a fine screw shown at the rear of the unit in Figure 6B.

The operating unit of OM_3 is identical with the M_3 unit. In order to produce the offset characteristic shown in Figure 4, a transactor is used as shown in Figure 7B. Transactor is the name that has been given to a reactor which has a secondary winding for a voltage several times that corresponding to the impedance drop produced in the transactor's primary winding, without increasing the burden.

The transactor in the OM_3 unit has double current winding, as does the operating unit, so that the voltage induced in its secondary winding is proportional to $I=I_1-I_2$ and leads I by 90 degrees. By connecting the proper amount of resistance R_4 across the transactor's secondary winding, the secondary voltage can be made to lead the primary current, I, by 75 degrees. The addition of this secondary voltage from the transactor in series with the potential transformer secondary



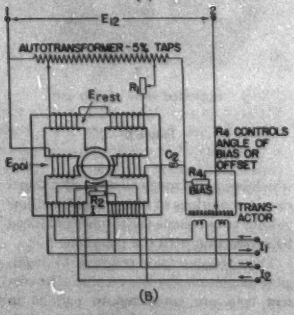


Figure 7

A. Diagrammatic wiring of M_1 and M_2 units
B. Diagrammatic wiring of OM_3 unit

Figure 8. Current in polarizing winding of M_1 unit during zero-voltage fault

voltage, which is applied to the relay terminals, results in a shift of the unit's ohmic circle so that it no longer passes through the origin. This shift, or offset, is a distance corresponding to (transactor secondary voltage)/(I_1-I_2) ohms at a 75-degree phase angle.

Adjustment of R_4 can be made to cause the offset to be along any angle between 75 degrees and 60 degrees to match the angular setting of the operating unit. The magnitude of the offset is governed by taps on the transactor secondary winding.

Characteristics

Each unit has been designed to meet the requirements of its use in either a purely distance relaying scheme or a directional carrier current scheme.

The M_1 unit is purely a directional distance unit. It has been designed to operate for faults out to 90 per cent of the line section and for swing conditions which cause the voltages near the two ends of its protected section to be 90 degrees out of phase. It is provided with connections for setting the angle of maximum torque on 75 degrees, 60 degrees, or 45 degrees. In order to operate properly in the presence of resistance added by arcing faults (Figure 9) it is expected that the 60-degree setting will be used most frequently. This setting is discussed more fully in a companion paper.[5] The 75-degree setting is intended for longer lines, the 45-degree setting for short lines.

The plotted points shown in Figure 4A illustrate the negligible deviation of the operating characteristics of the units in a typical relay from the theoretical mho circle, when rated voltage is applied. This circular characteristic is a result of the steady torque produced in an induction cylinder unit. Units whose operating forces are pulsating throughout a cycle do not produce a true circle, thus adding difficulty to the calculation of settings for obtaining accurate relaying during power swings.

As is common with distance relays, the accuracy falls off at low values of current (and voltage). Figure 10 shows that the contacts of an M_1 or M_2 unit will close under steady state conditions for any fault in the correct direction from zero ohms up to the setting of the unit, so long as the current is greater than the vicinity of seven amperes. At two amperes the contacts will fail to remain closed under steady state conditions for faults within the first five per cent or the last five per cent of the relay's setting. That is, the ohmic circle maintains a constant center, but becomes smaller. This change occurs because the torques caused by the control spring and friction are no longer negligible with respect to the electrical torques in the unit.

The curve in Figure 10 is valid for an M_1 or an M_2 unit on its minimum distance setting. For other settings the accuracy is approximately the same for the same value of relay voltage.

Figure 10 represents accuracy under steady state conditions. With a rapid seal-in unit, the tripping area for fault conditions will be expanded by contact closure caused by transient torques. For faults at the relay bus, the memory action produces a strong torque in the correct direction for currents down to five amperes. For faults a short distance beyond the setting of the M_1 unit, its contacts may close because of a phenomenon known as transient overreach. For this reason the M_1 unit is set to cover 90 per cent of the line section under steady state conditions, allowing ten per cent for such errors. The minimum reach of the M_1 unit for faults near the end of its setting is as shown in Figure 10, but the maximum reach will be approximately ten per cent

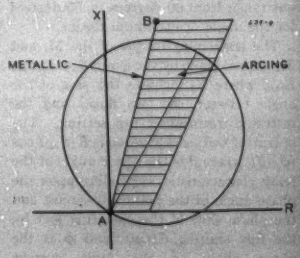
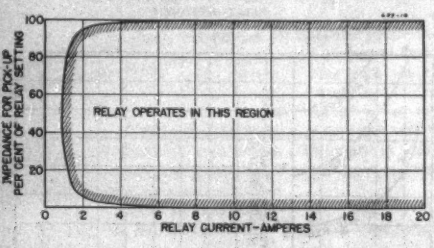


Figure 9. Effect of arcing fault

more. See "Transient Overreach" later in this paper.

The M_1 unit has correct directional discrimination for currents as low as 1.5 amperes at one volt and operates correctly for a period long enough to cause tripping when necessary for currents as low as five amperes on zero-voltage faults.

Figure 10. Steady state accuracy of M_1 and M_3 units



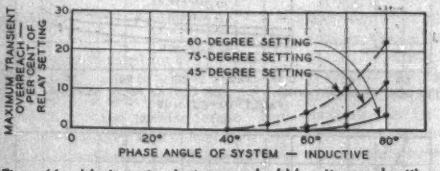

MAXIMUM TRANSIENT OVERREACH — PER CENT OF RELAY SETTING
60-DEGREE SETTING
75-DEGREE SETTING
45-DEGREE SETTING
PHASE ANGLE OF SYSTEM — INDUCTIVE

Figure 11. Maximum transient overreach of M_1 unit, normal setting is 60 degrees

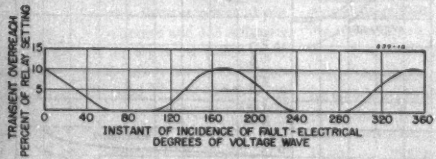


Figure 12. Variation of transient overreach in M_1 unit with instant of incidence of fault

The very small amount of transient overreach for this type of unit has been obtained at the sacrifice of some speed. Operating times of the M_1 unit are shown in Figure 13.

The M_3 unit is used with a short time delay in the timing relay to give the second zone of a distance relay setting, or it can be used as the directional relay to cause tripping in a carrier current relaying system. A large amount of transient overreach can be tolerated for either of these functions. Speed is important for the second function. Therefore the operating times have been made as short as possible (Figure 14), disregarding the transient overreach. The accuracy under steady conditions is the same as that of the M_1 unit, as well as the memory action at zero voltage.

If the OM_3 unit were used without using the transactor to obtain offset, it would operate exactly like an M_3 unit. In addition to the transactor, it has had a normally closed contact added.

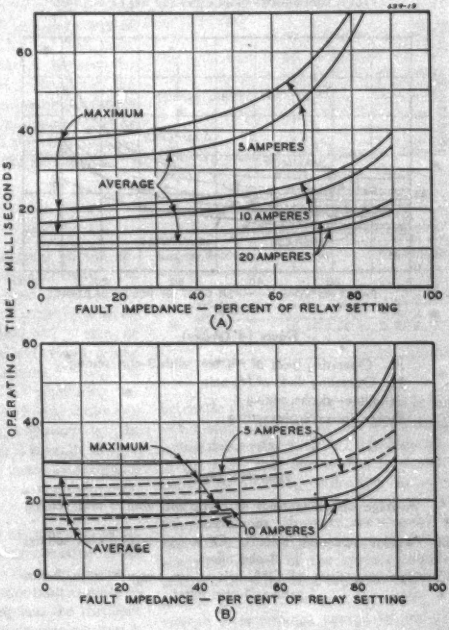


Figure 13

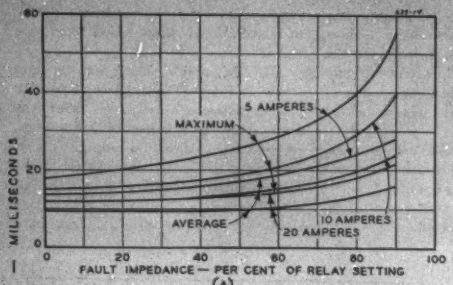
A. Operating times of M_1 unit with 3-ohm setting
B. Operating times of M_3 unit
Solid line—6-ohm setting
Broken line—12-ohm setting

The OM_3 unit is designed for use as a time-delay backup unit, for which accuracy is not important, and for use as a fault detector to start the carrier signal when carrier-current relaying is used. For this latter function, speed is very important. The normally closed contacts open in one-half of a cycle (60-cycle basis) for most fault conditions. In order to maintain them in their open position after the initial torque has disappeared for bus faults, it is necessary to use some offset.

Figure 15 shows typical operating times for the OM_3 unit. There are other conditions of distance setting and ohmic offset, but these same curves are approximately correct for the other conditions. Actual curves for the conditions not illustrated would show faster operating times.

The OM_3 unit's setting for the data shown in Figure 15 was three ohms with 1-ohm offset. This means that the ohmic circle has a diameter of three ohms, offset one ohm from the origin. Therefore the reach is two ohms in the unit's forward direction and one ohm in the offset direction.

The effect of the offsetting transactor is to introduce an operating torque proportional to the square of the current. In the offset direction, this I^2 torque has to overcome the torque caused by memory action, resulting in the increased operating times for faults in this direction. For this reason, it is necessary to use the reversed OM_3 connection whenever the OM_3 unit is used for starting a carrier-current signal.



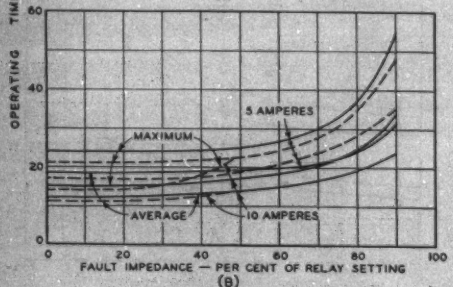
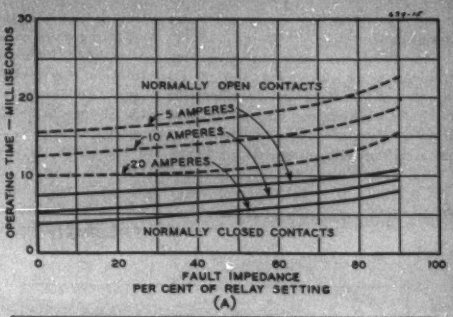
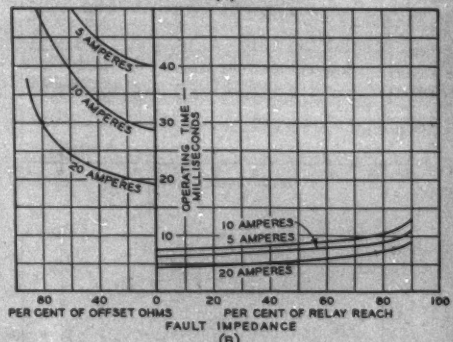


Figure 14 (above)

A. Operating times of M_3 unit with 3-ohm setting
B. Operating times of M_2 unit
Solid line—6-ohm setting
Broken line—12-ohm setting





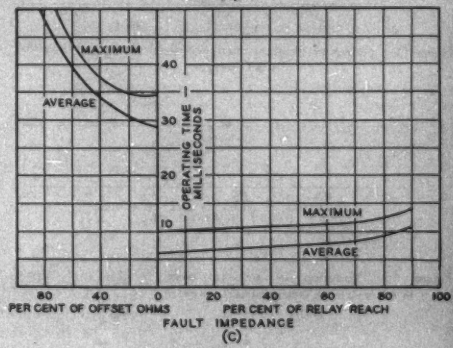


Figure 15 (right)

A. Average operating times of OM_3 unit with 3-ohm setting, zero offset
B. Average operating times of OM_3 unit with 3-ohm setting, 1-ohm offset
C. Operating times of OM_3 unit at ten amperes with 3-ohm setting, 1-ohm offset

Transient Overreach

The transient overreach of the M_1 unit mentioned under "Characteristics" is caused by transient conditions at the inception of a fault. These transient conditions may produce torque in the contact-opening direction, which will result in long operating times for faults within the setting of the unit. When the transient torque is in the contact-closing direction, the operating time is fast, and the contacts will close momentarily for faults a short distance beyond the setting of the relay.

The transients have been minimized in the potential circuits by the use of tuned circuits. The transients in the current circuit have been reduced for the 60-degree setting by the use of a capacitive flux shifting circuit. This reduction is illustrated by the small amount of overreach for the 60-degree setting in Figure 11.

Maximum transient overreach coincides with maximum d-c offset in the current wave. Thus in Figure 11, the higher the phase angle of the system, the greater the possible overreach. Figure 12 shows that for each half-cycle, faults initiated during the period which yields maximum d-c offset are most subject to overreaching.

This d-c offset can become quite large. For example, the equation for the short-circuit current of a fault occurring at the instant which produces the maximum d-c offset can be written

$$i = I(\varepsilon^{-(R/\omega L)\omega t} - \cos \omega t)$$

where I is the peak value of steady state current and the shunt capacitance is

neglected. For a 60-cycle system whose ratio $R/\omega L$ produces an 80-degree phase angle, this fault must occur at an instant corresponding to ten degrees before the zero of the voltage wave, and the current becomes

$$i = I(\epsilon^{-88.9t} - \cos 377t)$$

The first current maximum occurs at 0.0081 second and has a magnitude of $1.58I$.

Good current transformers reproduce transients accurately during the first half cycle so that this maximum value is transmitted to the relay. Some types of distance relays have operating forces proportional to the square of the current, thereby multiplying the transient operating force by a factor of 2.5 without a compensating increase in the restraining force.

A d-c offset in the current wave of such magnitude can introduce additional errors when an impedance characteristic is offset into a mho characteristic by using the current to reduce the restraining force.

Ratings

The relay is rated for 115 volts and 5 amperes. In order to achieve the utmost reliability, the mho unit was designed to have the greatest possible torque. Not only was memory action employed, but the input to the relay is as high as thermal conditions will permit.

The maximum burdens for a practical setting of the mho distance relays at one terminal for 5 amperes and 115 volts are approximately 40 watts per phase at 95 per cent lagging power factor in the potential circuits, and 17 volt-amperes per phase at 60 per cent lagging power factor in the current circuits.

The basic ohmic setting of the three units, M_1, M_2, and OM_3, is 3 to 30 ohms phase to neutral at the relay terminals. Where shorter settings are required, auxiliary current transformers with a tap providing a three-to-one or a two-to-one ratio are used to obtain ranges of 1.0 to 10 or 1.5 to 15 ohms respectively. This enables the relays to be readily interchangeable and at the same time permits a high setting of restraining torque on all relays and the utilization of the maximum torque permitted by thermal limits. The connections to these auxiliary current transformers are shown in Figure 5.

The current sensitivity decreases in direct proportion to the ratio of the auxiliary current transformer. For this reason the relay is not applicable to short lines with small short-circuit currents. All characteristics have been presented for the relay without the auxiliary current transformers.

The ohmic offset of the OM_3 unit can be set for zero, one, two, three, or four ohms, phase to neutral. When the auxiliary current transformers are used, these values are reduced to 0, 0.33, 0.67, 1.0, or 1.33 for the 1.0- to 10-ohm range, or 0, 0.5, 1.0, 1.5, or 2 for the 1.5- to 15-ohm range.

Although the relay is designed principally for angular settings of 60 degrees for the M_1 unit and 75 degrees for the M_2 and OM_3 units, provisions have been made for setting the M_1 unit on 75 degrees or 45 degrees, and the M_2 and OM_3 units along with the transactor between 60 degrees and 75 degrees. Changes in the angular setting change the ohmic ranges of the units, with the minimum values as illustrated in Table I, the maximum remaining at ten times the minimum.

Application Limits

There are two limitations on the applicability of the mho distance relay. On systems where a fault near the end of the M_1 unit's setting can result in a small value of current, the unit will be slow, or possibly fail to operate and delay tripping until the time for the second zone. On very short lines, there is a possibility that the resistance added by arcing faults will place the impedance, measured by the relay for a fault which is actually in zone one, to be outside the zone-two setting of the relay. These limitations are discussed in a companion paper.[5]

In some cases, the M_1 unit can be set on 45 degrees to allow for the effect of arc resistance. If this is done on a system whose phase angle under fault conditions is greater than 70 degrees, the transient overreach of the M_1 unit requires that it be set to protect less than 90 per cent of the line section.

Setting of the GCY Relay

The angular setting of the M_1 unit is by means of leads on a connection block as illustrated in Figure 7A. If the angular settings of M_2 and OM_3 are to be changed, they must be changed by test.

The procedure for setting the diameters of the ohmic circles is the same as the one which has been in use for the well established type GCX reactance relay. The output tap settings of the two autotransformers shown in Figure 7 are chosen according to the following formula (the M_1 and M_3 units use the same transformer):

$$\text{Percentage output tap setting} = \frac{\text{unit's minimum ohms} \times 100}{\text{desired ohms}}$$

The ohmic offset of the OM_3 unit can be adjusted by means of a lead on another connection block. The ohmic reach has to be increased by an amount equal to the ohmic offset to obtain the "desired ohms" in the formula.

Out-of-Step Blocking

As can be seen from Figure 4A, when the OM_3 unit is set to include the M_2 unit's setting, it will pick up on power swings before the M_2 unit. This characteristic can be utilized to recognize an out-of-step condition by the addition of a time delay relay such as *TB* in Figure 5. If the OM_3 unit operates at least four cycles, for example, before the M_1 unit, *TB* operates and can be used to open the tripping circuit. However, the mho unit's inherent characteristic of tripping at the electrical center of the system usually makes it advantageous to permit tripping and to use *TB* to prevent automatic reclosure after tripping caused by out-of-step conditions.

Table I. Change in Minimum Ohmic Setting at 115 Volts Versus Change in Angular Setting of Unit

Angular Setting	Minimum Ohmic Setting	
	M_1	M_2 and OM_3
75°	2.23–2.44	2.94–3.06
70°		2.83–2.97
65°		2.64–2.87
60°	2.94–3.06	2.37–2.78
45°	2.10–2.20	

Conclusions

1. A high-speed directional distance relay has been designed using a unit of the induction cylinder type so that it has an inherent directional characteristic and distance measuring accuracy, permitting one contact to protect 90 per cent of a line section.

2. A modification permitting transient overreach provides speed acceptable for use as a directional relay in carrier-current application.

3. The use of a transactor provides a quasi-impedance unit suitbale for starting a carrier signal and providing time delay backup protection.

4. A combination of the three units with a timing relay provides 3-step distance protection.

Metal-Clad Unit-Type Switchgear for 33-Kv Service

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Synopsis: The experience of the Public Service Company of Northern Illinois with metal-clad switchgear has been outstanding, both from the standpoint of reliability of operation and safety to personnel, two of the principal objectives sought by the engineers of the company when they pioneered this type of equipment. This equipment has been applicable not only to the voltage classes up to and including 15,000 volts, but also in the 33,000-volt class, of which the company has seven major installations which have been in service from 13 to 16 years. This report of experience with 33-kv metal-clad switchgear is offered as proof that development and use should be resumed and continued in what is undoubtedly a fertile field for the application of principles which are now generally accepted. It is not a detailed discussion of the design and construction of metal-clad equipment, but rather a factual record of progress already made and proved by 13 years of operating experience. Conclusions drawn from this report are that the main objectives sought after in the development of metal-clad type of switchgear have been obtained satisfactorily. Experience has demonstrated clearly its outstanding operating reliability as compared with the conventional open type, and its perfect safety record for operating and maintenance personnel has been made possible by the inherent safety features which are practical only in metal-clad equipment. If these and other factors which cannot be evaluated precisely are taken into consideration and if the further exploitation in the post-war period of materials and methods developed during the war is kept in mind, it would appear that there is no question about the continued development of metal-clad type of switchgear in all voltage classes. Repetitive manufacturing, standardization, and prefabrication are some of the most potent means of combating the continually rising cost of electrical station and substation installations. The electrical equipment manufacturers are applying these principles to a growing extent and are promoting their use throughout the industry. The principles, of course, are not new, the present movement being directed mainly toward a more intensive and wide-spread application. Neither the manufacturer nor the utilities can afford to neglect any application of these principles that can be justified economically.

IN the initial use of metal-clad equipment, the engineers of the Public Service Company of Northern Illinois had certain definite objectives in view. Subsequent operating experience has shown that very substantial advances had been made toward these objectives before progress was interrupted about 1931 by economic conditions. This experience indicates that development and use of this equipment should be extended to higher voltages.

The outstanding characteristics of the installations of all voltages made by the Public Service Company of Northern Illinois were complete enclosure in metal, maximum practical factory assembly, and the filling of all space in the enclosing structure with an insulating medium other than air. Various terms were applied to such equipment, the one in most general use being "metal-clad gear." The equipment of this nature now being manufactured and used is enclosed in metal and factory assembled but, with possibly a few exceptions, is not filled with an insulating medium. It also is designated by various terms, including "metal-clad." Complete enclosure and maximum factory assembly are fundamental, but the filling or nonfilling of the housing can be considered a matter of design keeping in view the objectives.

Objectives

Broadly speaking, the objectives of advantages to be obtained from metal-clad construction are Safety, Reliability, and Economy. The first two can be obtained without the third; the third cannot be obtained without the first two.

Safety of personnel is fundamental and needs no explanation.

Reliability can be considered as the quality of being available at all times for the service for which it was designed and rendering that service continually.

Economy is more involved than the other two main objectives and includes both, because no installation can be truly economical if it is not safe and reliable. Safety and reliability in themselves, however, are of sufficient importance to warrant special consideration. They do have a very real and substantial monetary worth, but it is impractical to assign a definite dollar value to it. Economy, therefore, is considered herein as the actual dollar expenditure in rendering service from a given installation. To obtain fair comparisons, economy must include the following cost factors:

1. First cost (manufacturer's cost to user).
2. Engineering, supervision, and overhead (user's).
3. Installation and transportation.
4. Maintenance and repair.
5. Operation.
6. Durability (life expectancy).
7. Space occupancy and appearance.
8. Salvage value.

History and Progress

For the purpose of determining what progress has been made in the attainment of the objectives, we can consider the history of the 33-kv installations as a group in reference to each objective.

5. The unit which causes instantaneous tripping for faults in the first zone can provide correct tripping during out-of-step conditions on most systems without auxiliary blocking relays.

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Figure 1. Typical 33-kv open-type structure

This shows installation used for cost comparison

Safety

There can be no doubt that working conditions are immeasurably safer on all of these installations than on conventional open-type installations. The safety factor is self-evident when it is considered that all current-carrying parts are enclosed in grounded metal and interlocks provided to prevent wrong operations and exposure of energized parts. Interlocking on metal-clad gear is entirely practical to an extent beyond possibility on open-type.

The prevention of inadvertent contact with energized parts can be accepted on the basis of the design. The proof, however, is negative because incidents occurring while working on metal-clad equipment, which would have caused an accident if the equipment had been open-type, are not recorded for the simple reason that there was no accident. An example of this is shown in the routine maintenance work of painting. Since 1928 there have been two accidents on 33-kv open-type structures, one resulting in a fatality and the other in an injury, definitely attributable to painting. These accidents could not have happened on metal-clad equipment. There is no record, of course, of painting in the wrong place on metal-clad because it can be painted while energized.

Since 1928, when the first 33-kv metal-clad gear was installed, to date there have been no accidents caused by inadvertent contact with energized equipment. This is also true of the lower voltage equipment, of which there are many installations on the system of the Public Service Company of Northern Illinois. Only one accident resulting in injury was recorded in this period. This accident was caused by burning oil from a ruptured box housing an oil-immersed disconnect switch. The switch blade fell into a ground clip because of the failure of an operating rod in one of the earliest installations. The failure definitely was caused by a defect in design which has been corrected.

During the same period, three fatalities and four injuries have occurred on open-type 33-kv equipment, all of which, except two of the injury cases, were caused by contact with energized conductors. One of the latter resulted from the failure of a bushing, and the other was the result of falling porcelain from an insulator which had failed mechanically.

Experience has shown that the metal-clad installations have a distinct advantage in reduction of nonelectrical accidents also, mainly by the elimination of the necessity of temporary staging and ladders or the climbing of complicated structures. When necessary, permanent ladders, platforms, and railings are provided easily.

Reliability

The same major characteristic which provides safety in metal-clad gear, that is, the enclosure of all current carrying parts, also gives it an inherent quality of reliability, since it excludes practically all foreign elements which interfere with normal operation, such as weather, animals, birds, deleterious gases, dirt, and solid objects. There is no need to cite the instances of outage or damage to open-type equipment from these causes; they are all too familiar. Two outstanding examples might be mentioned, however. One metal-clad installation is immediately adjacent to a railroad right-of-way, and, in addition to normal heavy traffic, locomotives stand for extended periods on a side track within 20 feet of the structure, which is sometimes obscured in smoke. It is doubtful if an open-type installation could be kept in service at this location. Just recently the Public Service Company of Northern Illinois was forced to remove an open-type 33-kv switching structure on account of many insulator flashovers caused by contamination of the air by an industrial plant one-fourth of a mile distant. It might be well to mention birds particularly, which are a source of trouble and expense in open steel structures. They build nests in enclosed structures also, but there they are merely an annoyance and not a hazard to service.

All of the 33-kv metal-clad installations made by the Public Service Company of Northern Illinois are still in operation and giving reliable service. There were, of course, operating difficulties at the start which are to be expected in any newly designed equipment, particularly in a radical departure such as 33-kv metal-clad was at that time.

Electrical Difficulties

The most serious of the problems arose in connection with the shell bushings which were mounted over openings in the bottom of the metal boxes or housing of the gear and served as the sockets for plugging in the oil circuit breaker. Thus, the inside surface of the shell itself was exposed to air while the outside was exposed to the oil in the box or compartment. The first 33-kv gear was installed in April 1928, and the first failure of a shell bushing occurred in March 1929 with others following. The fact that the failures usually occurred during a rising

Figure 2. Metal-clad installation used for cost comparison

atmospheric temperature or high humidity indicated that condensation on the surface of the shell bushings in the circular space between the shell and the breaker bushing was a contributing factor. This condensation was pronounced because the temperature of the mass of the gear lagged behind the rising ambient temperature. In some of the installations, the lower end of the shell bushing orifice was not closed entirely when the breaker was in place. In the other installations, the orifice was closed by a soft gasket on the base of the breaker bushing when the breaker was raised to operating position. As the shells which were open at the bottom gave by far the most trouble, it was supposed at first that dirt on the surface combined with the moisture from condensation was the cause of flashover, and a cleaning program was instituted.

It soon was noted that severe corona discharges were taking place within shells previous to failure, even to the extent of being audible and visible. It also was noted that these discharges started very soon after cleaning in some cases, particularly during a rapid rise in atmospheric temperature.

Investigation and tests were continued and led to certain conclusions. The bushings, although open to the air (breathing occurred through the gaskets even in those closed at the bottom), were not exposed to the cleaning action of the elements as were ordinary outdoor bushings. This condition was conducive to corona and surface leakage from the energized metal parts at the top and the formation of nitric acid when condensation supplied the water. Conducting paths thus were established, and the process was cumulative until breakdown occurred over the surface of the porcelain. A contributing factor was metal salts from the corrosion of caps and contacts at the top of the shell. As the deposits on the porcelain did not yield readily to ordinary cleaning, special methods involving the use of carbon tetrachloride, alcohol, and certain dilute acids were tried.

Actual failure from this cause occurred at the original installation only, although corona discharge was observed at other locations. The cleaning program prevented the discharges from extending to the point of failure.

The bushing assemblies in the various makes of switchgear differed considerably in detail, and these were studied further in an attempt to eliminate or at least reduce the cleaning required.

As mentioned before, it was assumed at first that the closing of the shells at the bottom would eliminate or at least materially reduce the trouble, and this was the first step taken. The manufacturer was reluctant but later agreed, and that change was completed on the first installation about September 1930.

The closing of the bottom of the shells, of course, was a question of exclusion of deposits from the atmosphere, and leaving them open was to allow circulation of air to reduce condensation. Neither result was accomplished, however. It was impractical to seal the opening tight enough to prevent breathing; and, although actual dirt might be excluded, air usually contains certain acids such as sulphur dioxide, particularly in cities or industrial centers. The circulation of air in the bushings left open was practically nil, as the only opening was at the bottom, and this was very restricted. Some shells are still open, others closed.

This all indicated that the opening or closing of the shell opening was not the answer to the problem. Accelerated time tests in the laboratory indicated all shells were subject to the formation of nitric acid and metallic salts from the slight corrosion of the metal parts at the top. To prevent the corrosion, lead gaskets were eliminated and plating of copper parts experimented with. Chrome plating was tried but was not entirely satisfactory, owing to the difficulty of getting a perfect homogeneous coating on the odd-shaped parts. Tinning all but contact surfaces, which were silvered, finally was adopted for the installations giving the most trouble. There still remained some defective porcelain in one installation and the short leakage distance and inability to clean entirely at

Figure 3. First installation of 33-kv metal-clad switchgear, showing overhanging removable potential transformers

another. These shells all were replaced finally with smooth instead of corrugated porcelain and redesigned contacts and corona shields.

While the changes stated have not eliminated the problem, they have provided shells with better characteristics and have lengthened the interval between cleanings. At present all 33-kv shells are cleaned each fall and spring with a weak solution of muriatic acid followed by thorough washing with a cleaning compound. This program has been followed for the past ten years with no further trouble.

Other than the shell bushings, only one electrical weakness affecting reliability developed. This also was in the first installation and resulted in two cases of bus failure to ground. The bus in all the installations is copper tubing insulated with machine-wound impregnated paper or fabric and supported at intervals centrally in an outer copper pipe by spools of insulating material. The space in the outer pipe around the conductor is filled with oil. The spools at first were turned from a laminous material of pressed paper; later spools were of porcelain or paper wound directly on the conductor insulation. The first theory was that minute drops of water from condensation had collected at the bottom of the bus pipe under the spool, concentrating the electrical stresses and forming creepage paths that resulted in final failure. The manufacturer recommended circulating the oil and heating at intervals to remove moisture, and this was done for a short period. The process was rather expensive and critical, however, as it was necessary to maintain the oil temperature within rather close limits, that is, high enough to remove moisture but not high enough to cause sludging. After the second failure, notice was taken of the fact that although the spools were in halves held around the conductor by cord, the failure was not at the junction of the halves but directly through the spool and parallel to the laminations where they were radial. As previously stated, these spools were turned from a laminated material. This indicated that creepage started between the laminations, and the spools were replaced with a non-laminated material. There have been no failures since, and circulation of oil was discontinued.

It should be noted that neither of these failures caused any damage beyond a small hole in the insulation and outer copper tube and loss of oil in one bus section. There was no fire in either case. The failure was direct to ground. The bus was protected by bus fault relays.

The only actual failure since the early ones mentioned occurred in 1939, and the indications were that it originated with the oil circuit-breaker bushing. In this respect the failure was similar to those occurring in open-type gear. As the breaker was mounted in metal-clad gear, however, the effects must be noted. The failure was in the annular space between the oil circuit-breaker bushing and the shell on the bus side of a line position. Both shell and bushing were fused and burned, severely, typical of an external flashover. The shell was cracked severely but remained in place. The cracking, however, permitted oil to flow into the annular air space between bushing and shell, where it was ignited by the arc and blown out of the shell orifice at the bottom across the top of the breaker, forming an external oil fire which continued after the arc was extinguished. Since the oil burned as it flowed down the wall of the inspection bay before it was extinguished by the gravel bed at the ground level, the fire was more spectacular than damaging. The loss was limited to the breaker bushing, the porcelain shell, the escaped oil, and scorched paint. There was no internal damage to the gear or breaker.

The weather was clear, warm, and dry, which eliminated excessive condensation as a contributing factor as in the earlier troubles.

It was difficult to determine definitely whether the failure originated across the shell or the bushing. There was some evidence of a very slight oil leak at the top of the shell through a defective gasket which formed an oil film on the surface of the shell to which air-borne particles might have adhered and gradually decreased the creepage distance to ground. On the other hand, the particular type of bushing used had been the source of trouble in open-type equipment. The pertinent question for this discussion, however, is whether the failure was the result of or indicated any inherent weakness in the basic hypothesis of the type of installation. Neither the faulty gasket nor the faulty bushing would indicate this. They were both representative of the occasional freaks encountered at

times in any type of construction. Preventive measures against recurrence are the same in this case as for conventional open-type equipment, that is, greater care in fabrication, inspection, and testing and faster relaying to limit fault duration.

It also should be noted that only features peculiar to the type of installation are considered here. For example, there were certain troubles with oil circuit breakers, but these were of the type common to both metal-clad and open-type construction.

Mechanical Difficulties

Early experience with the first installations naturally disclosed certain mechanical features which were undesirable or troublesome. None of these was an insurmountable difficulty, nor did the remedy force any basic changes in design.

Soon after the first installation was made, some shell bushings developed circumferential cracks at or close to the upper edge of the bottom metal mounting ring which was cemented to the outside of the porcelain. This had no bearing on the electrical failures and was purely a mechanical problem. The metal mounting flange and cement, of course, were on the outside (oil side) of the shell, so the ring gasket was placed under the lower edge of the porcelain. As the bolt circle was outside of this gasket, a cantilever strain was imposed on the porcelain which was enhanced by slight inequality in tightening the bolts. A very slight shock or misalignment at the top of the shell then could easily cause the crack. The condition was remedied in the new shells by making the relation between the lower edge of the porcelain and the mounting surface such that there was metal-to-metal contact between the mounting flange and the mounting surface. This equalized and limited the strain on the porcelain. This condition existed at certain installations only, as the shells in the other installations were mounted with the flange below the mounting plate.

The only mechanical failure that was at all serious in its results was the breakage of the operating rod on an oil-immersed disconnect switch mentioned previously. As stated, this was remedied by proper design.

Some difficulty was encountered at first in preventing leakage of oil. The various boxes and enclosures in the first installation were of welded steel plate with flat covers and flat cork gaskets. It was soon evident that these gaskets, if not confined, would spread and set, permitting seepage of oil. Further tightening of bolts was only a temporary cure and soon reached its limit. After trials of other gaskets, it was found that a cork gasket confined in a groove and compressed by a tongue gave satisfactory results, and gaskets in later gear were so designed. To change the original flat gaskets to the confined type, however, was impractical and further trials were made ending in the use of a cork or other soft gasket with a thin soft metal sheath. The original gear was equipped with this type several years ago, and oil leaks and seepage have ceased. There was also some oil seepage through welds on boxes and directly through the metal of cast boxes used on the later installations. Tinning of the inside of welds and the inner surface of cast boxes prevented this seepage. Improved welding and the use of different material for cast boxes made tinning unnecessary. This matter of oil leaks and seepage is largely a question of appearance, as in no case was it sufficient to reduce the amount of oil in the gear to any appreciable extent over a very considerable period.

Figure 4. Installation of 33-kv metal-clad switchgear with main and transfer bus

The availability factor of reliability is influenced materially by ordinary routine maintenance requirements. In open-type installations, it is necessary to take out of service major portions or even an entire structure for such work as cleaning or replacement of insulators, painting, and lubrication of moving parts. Frequently busses or lines not being worked on must be de-energized to provide proper safe working clearances. This class of maintenance, with the exception of the semiannual washing of shell bushings mentioned previously, requires no outage of metal-clad equipment. Even an outage for cleaning is reduced to only the particular line or bay directly concerned.

Economy

First Cost. First cost, of course, is a manufacturing problem involving design, fabrication, and assembly. This factory assembly is of major importance. It increases first cost of metal-clad above equipment for a comparative open-type installation but reduces field installation costs, and we are considering over-all economy, as mentioned before. The seven installations made by the Public Service Company of Northern Illinois covered a period of only about three years and were fabricated by three different manufacturers. Naturally, first cost was somewhat high because of development charges and because effort was concentrated on design for safety and reliability rather than cost of manufacture. There was considerable variation also in price among different manufacturers and among different installations by the same manufacturer because there was no background of experience on which to base manufacturing costs.

Each of the installations made was an individual development and did not approach even the first phase of being on a production basis. Two manufacturers built two installations each and one manufacturer built three, and naturally any part or feature developed for the first was used wherever possible in the second. This possibility was exceedingly limited, however, owing to changes in detail design. There were only two major changes in design made during the period which might affect first cost. One was the manner of connecting and mounting potential transformers, and the other was the use of cast boxes or compartments in place of welded plate. In the original installation, connection boxes overhung the structure and were provided with shell bushings permitting the potential transformers to be raised into place or lowered the same as the oil circuit breakers by means of a special traveling elevator on the structure. In all subsequent installations, the potential transformers were connected solidly and mounted in boxes as an integral part of the gear with an arrangement for replacing fuses. This eliminated many shells and bushings as well as an elevator. The use of cast boxes not only affected the cost of the boxes themselves but provided round cover flanges and covers into which it was cheaper to machine grooves for confined gaskets.

A major factor in the cost of any installation is the bus and switching arrangement. Two common variations are complete double bus with two oil circuit breakers per circuit and main and transfer bus with one circuit breaker per circuit. In the latter a breaker is usually provided for energizing the transfer bus from the main bus with section breakers or disconnect switches in the main bus on each side of this feed to permit taking part of the bus out of service for maintenance or keeping part in service in case of bus failure.

The first installation was a double bus arrangement, however; only one circuit breaker was provided for each of two transformer circuits. This possibility of reducing cost and still retaining the advantage of a double bus because the breakers were movable from one bus position to another, a condition which does not exist in conventional open-type construction.

The installation which followed was a main and transfer bus arrangement. There were two reasons for this: first, the available space was limited in width, and only one breaker per bay resulted in a narrower structure; second, it provided a practical trial of that particular bus and switching arrangement as applied to that type of equipment. This required the development and use of enclosed oil-immersed disconnect switches, which present certain problems. While this arrangement reduced the cost per bay, the total cost was not reduced materially because of the provision of two bus section breakers and the transfer bus feed breaker. As equivalent operating facilities at little additional cost could be provided by a double bus arrangement with only one breaker per circuit in some cases, all subsequent installations were built according to this arrangement. The moving of a breaker of any line or transformer position by means of the motor-driven elevator from one bus to the other is comparable to the operating of disconnect switches for connecting a line or

Figure 5. One of the later installations in a residential district

Ornamental brick wall enclosing property is shown

transformer to a transfer bus in open-type structures.

Engineering. The engineering ordinarily considered as preliminary, such as determination of necessity, number, capacity, and location of lines, feeders, and equipment, can be considered as equal in cost for both types of equipment if we forget for the moment an advantage of metal-clad equipment in the matter of location. What might be termed construction engineering follows. For an open-type installation, this consists of considering, specifying, counting, ordering, listing, and delivering to the job various pieces of major equipment and innumerable items for connecting and mounting. Construction specifications and many drawings must be prepared for the assembly of all these parts into a satisfactory structure. For metal-clad equipment the user need specify but one piece of equipment, and very few drawings are needed for installation, thus reducing his engineering costs materially.

It is true that much of the user's engineering cost is transferred to the manufacturer and must be included in first cost because the manufacturer must design and assemble the various parts of the unit. These costs should be considerably less, however, when this work is done by the manufacturer because he is designing and assembling many units, while the user must design each unit for himself. Factory assembly is inherently cheaper than field assembly for several reasons, freedom from weather interference being one.

This, of course, assumes a certain degree of standardization, and metal-clad equipment lends itself to this standardization to a far greater extent than open-type. Standardization in conventional design more usually is limited to component parts.

Installation. Field installation is where metal-clad equipment must show the greatest reduction in cost as compared with open-type. Again consider the innumerable small pieces of an open-type structure which must be assembled piecemeal contrasted with the very few large parts of metal-clad. Here again design plays a major role.

When the first installation was purchased, the goal of unit assembly was in the minds of those concerned. Experience had been had with lower voltage gear, and design changes had brought this to the point where even complete bus sections were shipped and installed as a unit. At that time, to assemble even one bay of a 33-kv structure into a single unit which would be within railroad clearances appeared impossible, at least to the manufacturer, and the first gear was shipped in many parts which were assembled on the job. The installation cost was the highest of any of the installations. As a result of much consultation with manufacturers, a design was worked out which enabled the next installation, which was a main and transfer bus arrangement, to be assembled at the factory and shipped in units of one bay as were all subsequent installations. The component parts as shipped from the factory were the main bay assembly (containing busses, instrument transformers, cable terminals for outgoing circuits, and all connections), the supporting columns on which the bay assembly was mounted, the circuit breakers, and the traveling elevator for raising and lowering breakers.

The next installation having a double bus was shipped assembled, and the complete cost of installation per bay was slightly under 25 per cent of the cost of the first installation.

Transportation of large pieces in carload lots from one point of shipment is more economical than many pieces from many different points for equal distances and total weight. Note also must be taken of the increased cost of following and co-ordinating the receipt of numerous items of equipment required for an open-type structure as compared with factory-assembled units.

An element of cost exists in many installations which does not appear in the cost records. This is elapsed time as distinct from man-hours. There frequently is a very definite saving in meeting a service date or a definite loss in not doing so which is distinct from the actual dollar cost of the installation. Metal-clad equipment has a definite advantage here which will be enhanced by more extensive use and standardization.

As an indication of what was done and what experience was obtained, some of the design features which made unit assembly possible should be mentioned. The unit-type principle must be in mind at all times in design. Considerable study was required so to design the various boxes and compartments comprising the main section as to permit an arrangement compact and rigid enough to make shipment by rail practical. These assemblies or units were shipped complete and filled with oil. The breakers were shipped separately, as they would be removed from their operating position in any case for test and inspection before being placed in service.

The busses presented another problem, as they, of course, extended the length of the structure to form a continuous conductor across all bays. In the first installation, the busses were received entirely separate from any other part and not even complete in themselves. The insulated tubing was in lengths which did not coincide with the width of bay. For subsequent installation, a satisfactory joint was developed for both bus conductor and enclosing tube that could be used at the junction of any bay, a development which permitted all complete busses to be mounted on each bay in the factory ready for connection to busses of an adjacent bay. These joints and other parts were so designed that all mechanical erection could be completed before any electrical work was necessary. Even control and secondary wiring was in place and brought to terminals for connection to the wiring from the control board.

Maintenance and Repair. Maintenance and repair were discussed under the preceding subjects of safety and reliability, and the same factors in metal-clad equipment which increase safety and reliability over that of open-type decrease the direct cost of maintenance and repair. Practically all ordinary routine maintenance such as painting, cleaning, and lubricating, can be performed on metal-clad without removing any part from service. This is seldom true on open-type, and for this reason much of this work is done at night or on Sundays or holidays when lighter load conditions are such that equipment can be taken out of service. This involves overtime which greatly increases the cost.

Repairs are necessary as a result of failure, deterioration, or wear. It is obvious that cost of repair decreases in proportion to increase of reliability.

Operation. If the presence of operators is required at a given substation, these costs will be equal for both types of installations. Metal-clad equipment, however, is more adaptable to control from remote points because of the absence of open disconnect switches and complete protection from interference by the elements.

Durability. The life expectancy of metal-clad equipment is much greater than open-type. The only part exposed to the weather is the enclosing metal structure. Organic insulation, if used on conductors, is not even exposed to the air. All of the 33-kv gear installed by the Public Service Company of Northern Illinois is oil-filled and equipped with

Figure 6. One of the later installations, showing method of enclosing transformer connections

conservator tanks similar to those commonly used on transformers. Experience has shown that oil deterioration is not a problem, as practically all of the original oil is still in service in the gear. There has been no filtering or treatment of any of this oil except that following the failure of the bus insulators mentioned previously, and as stated, that was unnecessary. This of course refers only to the oil used primarily as an insulating and filling medium in the various bus tubes and connection compartments. This oil is far less subject to factors causing deterioration than oil as ordinarily used in transformers or circuit breakers.

After from 13 to 16 years of service, all seven installations can be considered practically in the same condition as when new.

Space Occupancy and Appearance. Here again metal-clad has a very definite advantage, and if space is at a premium, the savings could be considerable. One of the installations, for example, could not have been made at its present location as an open-type structure. It was an old substation site very close to the center of town, bounded on one side by a steam railway and on the other by an electric railway. An open-type 33-kv structure would have required a new location at some distance, involving large costs for new property and building and also new transmission and distribution facilities.

At one location two metal-clad bays were added as an extension to an existing open-type structure and afford a striking comparison. The bays in the open structure occupy 729 square feet each, while the bays in the metal-clad structure occupy 605 square feet each, a saving of about 17 per cent. The height of the open structure is exactly 27 feet; that of the metal-clad is exactly 22 feet. This is not the entire story, however, as there are open disconnects and wiring on the outside of the open structure which require proper clearance and operating space. At one of the installations, there are six double bus bays and an inspection bay, and the structure from the center line to the center line of columns is exactly 90 feet long by 20 feet 8 inches wide. An enclosing fence placed three feet from the center line of columns would give ample space for all operation and inspection. (It could be on the columns if necessary.) Using the 3-foot space, however, gives an enclosed area of exactly 96 feet by 26 feet 8 inches, or 2,560 square feet. An open structure for controlling the same number of circuits would be exactly 108 feet long by exactly 36 feet wide based on the bay size of existing structures, and an enclosing fence should be at least ten feet from the center line of columns (usually it is more). This gives an enclosed area of 7,168 square feet, 2.8 times that required for metal-clad including the inspection bay.

Appearance has a definite economic value in public relations and also an indirect value similar to the space factor by permitting installations at locations where an open structure would be objected to by adjacent property owners. A metal-clad structure does not have the raw and unfinished appearance of an open structure, and if necessary can be camouflaged much more easily by architectural features or landscaping.

Salvage Value. Substation and equipment replacements in a great majority of cases are required by inadequate capacity because of load and system growth or changes. Retirement charges are high unless equipment for which the duty has become too great can be reused where the demand is smaller. This involves removal and reinstallation, and with an open-type structure, the same factors which cause high labor costs in installation also cause high cost of removal. An open-type structure must be dismantled completely to be relocated; and while the major items of equipment can be moved without loss, there is usually considerable retirement in connection with such items as structure, conductors, supports, control conduit, and wiring. A unit-type installation is moved in complete units as at first installed, with no retirement of material or equipment as far as the structure itself is concerned. The retirement of connecting cables and foundations would obtain in either case.

Comparison of Costs. A detailed study of the actual installed costs of one of the metal-clad installations and a comparable contemporary open-type structure gives the following percentage costs for the metal-clad, the cost of each item of conventional open-type being considered as 100 per cent:

Material cost per bay	145.4%
Labor cost per bay (including engineering)	62.6%
Foundations per bay	60.6%
Total installed cost	131.5%

This comparison is made on the actual dollar expenditure only and includes only the first three factors of over-all economy heretofore mentioned. Any reasonable evaluation of the remaining factors should more than offset the additional dollar cost of the metal-clad installation. In addition it must receive a very substantial credit for the high degree of safety and reliability in order to arrive at true over-all economy.

Future Development

In the foregoing discussion, the difficulties and faults of the present 33-kv metal-clad installations are covered in some detail in order to show that these difficulties and faults were overcome and eliminated. There is some accent on the

original installation because it was the first developed and furnished the experience for improvements in those which followed. The possibilities for further improvement, however, are by no means exhausted, particularly in the field of economy.

In future design the possibility of eliminating all shell bushings should be considered. All present installations are arranged with what might be termed removable or plug-in circuit breakers with a rather expensive motor-operated carriage elevator for raising, lowering, and moving them to an enclosed bay at the end of the structure. It is questionable if this is necessary. If the breakers are underhung as an integral part of the structure with a device for lowering tanks only, practically all maintenance and repairs could be accomplished. The gear structure would afford far more protection from the weather than is obtained for breakers in open structures unless temporary enclosures are built. If necessary, it would be a relatively small matter to provide a temporary enclosure on the sides of a metal-clad structure. If desired, this enclosure might be made permanent and enclose the entire lower part of the structure. This also will eliminate the inspection bay and reduce materially the cost of the transfer carriage.

If the breakers are in a fixed position, it will be necessary to provide means for entirely disconnecting them while they are being worked on. The first thought for this is an oil-immersed or enclosed disconnect switch, which is not difficult in itself but which presents certain problems in safety and operation. Being enclosed, the actual opening in the circuit cannot be observed and checked, and reliance must be placed on the operating mechanism or some other indicator. Indicators can be devised which are independent of the operating mechanism and in case of failure or breakage will not give a safety signal. Glass windows have been tried to provide direct view of the disconnecting device but are not always practical, particularly when looking into an oil-filled compartment. There may be a possibility in some of the new plastics in this connection. Even though the break will be visible, there is still the question of possible breakdown across the gap in a disconnect of this sort. A metal (grounded) barrier across the gap may be a solution.

The use of standard forms of cable for busses and connections should be considered as a possible means of reducing the cost and the amount of oil if oil is used.

The means for replacement of potential-transformer fuses can be studied to good advantage, as they are rather complicated and expensive. The reliability of present-day potential transformers suggests that primary fuses might be omitted, a factor which would be a major simplification.

The question of the necessity of an external terminal for testing, phase flashing, and so forth, should be considered. Such a terminal was provided on one of the installations, but in order to maintain the highest degree of safety, rather complicated interlocking on the various disconnect and grounding switches was involved. It must be remembered that as soon as exposed terminals which can be energized are introduced, the high degree of safety provided by entirely-enclosed metal-clad gear is lowered.

Recent development in the production of light metals opens up possibilities of reduction of weight and lowering of handling and installation costs.

Experience with gaskets enclosed in soft metal indicates that recessed gaskets may be eliminated.

Conclusions

From this discussion and the experience which it records, certain definite conclusions may be drawn:

1. Totally enclosed metal-clad construction provides the maximum degree of safety for personnel in the operation of electrical equipment.

2. The reliability of totally enclosed metal-clad equipment is far greater than conventional open-type.

3. While over-all economy of totally enclosed metal-clad equipment has been obtained, there are many possibilities for further advancement toward this objective.

4. Thirteen years of operating experience with seven different installations confirms the above conclusions.

5. A great advancement toward the objectives of safety and reliability in electrical equipment having been made, the research, engineering, and labor expended in making that advancement should be further exploited by continuing the development and use of totally enclosed equipment for voltages of 33 kv and above.

6. The present use of factory-assembled enclosed units indicates that the manufacturers have accepted the principles involved. The lack of development for higher voltages apparently is caused by the high first cost.

7. Metal-clad unit-type factory-assembled equipment for 33 kv is highly adaptable to standardized quantity production, and proper development will reduce first cost as well as over-all cost.

8. This development offers a definite possibility of combating the steadily rising cost of conventional construction.

9. The above possibility warrants earnest co-operation between manufacturer and user.

Induction Heating of Long Cylindrical Charges

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Synopsis: With the remarkable expansion of induction heating applications during recent years, a growing number of persons is being involved in the design and operation of induction heating equipment. While the general principle of induction heating is obvious to most, the concepts of certain important peculiarities such as skin effect, including its bearing on the intensity of heat generation, are not as widely understood. One reason for this state lies in the classic approach by partial differential equations[1,2] involving operations with which many engineers interested in induction heating are not familiar. A previous paper by the author offered a new approach for the analysis of the induction heating effect by using concepts commonly applied to a-c engineering and not involving differential equations.[3] A limitation of that paper consisted in the assumption that the radius of the charge will be very large in comparison with the so-called depth of penetration. It is the object of this paper to cast off this limitation and hence provide an analysis which is valid for any size of the radius of the charge and the depth of penetration. The generated heat is expressed in terms of rapidly converging series. The analysis is applied finally to the case where the charge is subdivided into a number of cylindrical rods. It is shown that for one certain radius of the individual rods, the inductor efficiency reaches a maximum. While in the case of a single (not subdivided) charge, the inductor efficiency cannot increase over a certain limit depending on the material of the charge, the subdivision of the charge removes such limitation, and inductor efficiencies can approach asymptotically 100 per cent for any material.

THE BODY to be heated is called the charge and is exposed to an alternating magnetic flux produced by an inductor, for instance a solenoid, which is energized from an a-c generator of suitable frequency (Figure 1). The alternating magnetic flux induces voltages within the charge. As a result, currents, the so-called eddy currents, flow through the charge and produce I^2R heat. Because the heating effect is originated by voltages generated by induction, it is called heating by induction, or induction heating. Heat also may be produced by hysteresis in the case of ferromagnetic materials at temperatures below the Curie point. For a large majority of practical applications of induction heating, the hysteresis loss is negligible and will be disregarded in the following.

Viewing the calculation of the generated heat as the final objective, the first step will be to compute the intensity of the eddy currents and their distribution within the charge.

For a cylindrical charge, the direction of the induced electric field intensity is perpendicular to the radius r, hence the eddy currents follow circles, whose centers coincide with the axis of the charge (Figure 2). The circles are positioned in planes perpendicular to the axis; if the ratio of length to diameter of inductor and charge approach infinity, the magnetic field intensity produced by the current in the inductor is uniform inside the inductor, while the magnetic field intensity on the outside of the inductor is zero.[4] Voltages and eddy currents will be the same along lines parallel to the axis. It follows that a slice cut out of the charge perpendicular to its axis is representative of the state of the entire charge.

Since the voltages and the eddy currents follow concentric circles, and thus have no radial components, a subdivision of the slice into a number of sleeves all telescoped into each other will not change the state of the slice, even if the sleeves were insulated from each other. In order to obtain uniformity of induced voltage and eddy current over the cross-section of the sleeve, its radial thickness is assumed infinitely small; consequently the number of sleeves is infinitely large. The charge thus is reduced to a (infinite) number of electric circuits amenable to quantitative circuit analysis.

Because of the resulting simplification in the analysis, the ratio of length to diameter of inductor and charge will be assumed approaching infinity. A very simple relation between magnetic intensity and ampere-turns per centimeter then results. In practical cases where the ratio of length to diameter of inductor and charge is finite, the spreading of the flux at the ends of the inductor results in a weakening of the induction, hence the formulas derived for the infinite case will give too high values for the generated heat.[5,6,7] However, as the ratio of length to diameter increases, the deviation from the infinite case becomes less and approaches zero asymptotically.

The analysis utilizes two different methods of approach, depending on the ratio between the radius a of the charge and the depth of penetration p. Each method has its special usefulness in its region of application, the border line between the two cases being at a ratio of $a/p = 3$. The results obtained by these methods are identical with the power

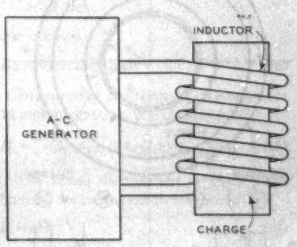

Figure 1. Arrangement of inductor and charge

series of Bessel functions, obtained as solution from an analysis based on partial differential equations.[2]

Case $a/p < 3$

For this case the eddy currents in the charge are calculated by a method of successive approximations. As previously explained, the charge can be reduced to a number of electric circuits. Suppose the charge is now slotted radially from the surface to the axis. All circuits in the slice become open. When such a fictitious charge is inserted into an energized inductor, open circuit voltages will appear across the slots of the various sleeves; the slots, however, prevent eddy currents from circulating through the sleeves.

Suppose the slots are now closed. Eddy currents start to flow through the sleeves, and it will be assumed as a first approximation that the eddy currents are given by the open circuit voltages of the various sleeves, divided by the electrical resistance of the respective sleeves.

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The actual eddy currents will differ from those thus obtained for two reasons:

1. According to Lenz's law, the eddy currents tend to weaken the magnetic field produced by the inductor, resulting in a reduction of the open circuit voltages.

2. Voltages of mutual reactance are induced in the various sleeves by eddy currents circulating in other sleeves.

In order to obtain a second approximation, the magnetic field distribution as determined by the first approximation is calculated. A new group of voltages is induced in the charge, which, in combination with the resistance of the sleeves, cause a new set of eddy currents to circulate through the sleeves. These voltages and eddy currents obtained by the second approximation are much smaller in magnitude than those obtained by the first approximation. The total eddy currents in the charge, thus far considered, consist of the sum of the eddy currents of first and second approximation. The actual eddy currents again will differ from those thus far obtained because the eddy currents of second approximation will weaken the previous magnetic field; moreover, voltages of mutual reactance are induced in the various sleeves by the eddy currents of second approximation, circulating in other sleeves. It will be noted, however, that the weakening of the magnetic field by the eddy currents of second approximation is of far lesser degree than previously encountered by the eddy currents of first approximation. Equally reduced in magnitude are the voltages of mutual reactance as a result of the eddy currents of second approximation, compared with the voltages of mutual reactance as a result of the eddy currents of first approximation. Further approximations can be obtained by proceeding in analogous fashion. This process leads to a power series which will be found to be rapidly convergent.

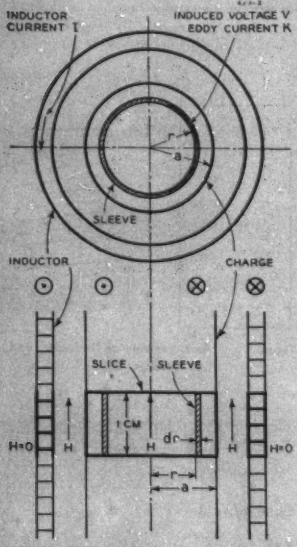

Figure 2. Sectional view of inductor and charge

Positive directions were assigned to the magnetic field intensity H and to the current I in the inductor. They are shown (Figure 2) by arrows parallel to the axis of the inductor and by the head and tail symbols, respectively, indicating a right-hand system. For alternating magnetic intensities and currents, the arrows show the direction of the instantaneous values, provided the latter appear positive in their respective vector diagrams. For a charge inserted into the inductor, the same positive directions are retained for the magnetic intensities H and currents K in the charge.

The magnetic-field intensity, henceforth abbreviated magnetic intensity, follows for an empty inductor from

$$H_o = 0.4\pi I_o n \tag{1}$$

A cylindrical charge is now inserted into the inductor. The induction B_o in the charge (caused by the inductor field) equals

$$B_o = \mu H_o \tag{2}$$

The magnetic flux Φ_o, which is surrounded by a sleeve with the radius r, equals

$$\Phi_o = r^2\pi B_o \tag{3}$$

As a result of Φ_o, voltages V_o, and hence eddy currents K_o, are produced in the charge. The eddy currents, however, produce magnetomotive forces of their own, resulting in the weakening of the original flux Φ_o, and in the induction of voltages in the various sleeves by mutual inductance. These effects of the eddy currents are nullified by introducing a so-called compensating current in the inductor, which is to offset the weakening action of the eddy currents with respect to the flux Φ_o, and furthermore by introducing compensating voltages in the sleeves. The latter voltages are connected in series with each sleeve and develop a voltage equal in magnitude and opposite in sign with respect to the voltage induced in the sleeve by the eddy currents in the charge and by the compensating current in the inductor. Under these assumptions the current I_o in the inductor produces a flux Φ_o (equation 3) which in turn induces a voltage V_o in the sleeve, as expressed conventionally by

$$V_o = -j\omega\Phi_o 10^{-8} \tag{4}$$

where

$$\omega = 2\pi f \tag{5}$$

Utilizing equations 1 to 5, V_o follows as

$$V_o = -j8\pi^2 10^{-9}(\mu f)(I_o n)r^2 \tag{6}$$

It is apparent that the radial distribution of the induced voltage V_o is parabolic. The slice is shown in Figure 3, looking in the axial direction. The magnitude of V_o as a function of the radius is shown by the graph superimposed on the view of the slice.

Before analyzing the implications of equation 6, it will be well to remember that the flux Φ_o also will induce a voltage in the inductor. If the object is to determine the voltage induced in the inductor by the entire flux inside of the charge, the variable radius r in equation 6 is replaced by the outside radius a of the charge. The voltage per turn of the inductor, caused by only the flux within the charge, follows from equation 6

$$E_o/n = -j8\pi^2 10^{-9}(\mu f)(I_o n)a^2 \tag{7}$$

and the voltage E_o per centimeter axial length of inductor is

$$E_o = -j8\pi^2 10^{-9}(\mu f)(I_o n)a^2 \tag{8}$$

It should be observed that other voltages are induced additionally in the inductor. There are the voltages resulting from the magnetic field within the inductor conductor and caused by the magnetic field in the air space between inductor and charge. Furthermore, an ohmic voltage component exists because of the copper loss in the inductor. The current in the inductor, multiplied by the various voltages listed, indicates the true and reactive power spent in the various parts such as the inductor proper, the air gap between the inductor and the charge, and the charge itself. Since this discussion is concerned only with the power requirements introduced by the charge itself, voltages induced in the inductor by parts other than the charge do not require further attention.

Returning to the voltage V_o (equation 6), currents, the so-called eddy currents, will flow in the sleeves as a result. The magnitude and phase of the eddy currents

are controlled by the voltage V_o, the resistance of the individual sleeve and the voltages induced in the sleeve by self inductance and mutual inductance.

While the voltage of self inductance is zero because the infinitely small cross-section of the sleeve multiplied by a finite current density (amperes/centimeter^2) results in a current (in amperes) of zero magnitude, the effect of the voltages caused by mutual inductance has been eliminated temporarily by the inception of sources called compensating currents and voltages, as previously indicated.

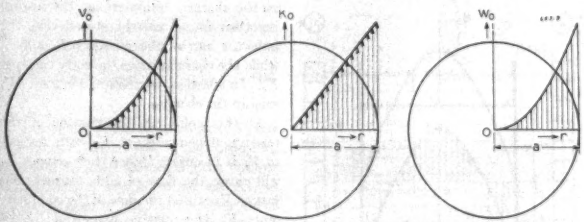

Figure 3. Radial distribution of induced voltage V_o, eddy current density K_o, and generated heat W_o

The eddy current is now solely a function of V_o and the resistance of the sleeve.

If the slice has a height of one centimeter, the resistance of a sleeve of infinitesimal thickness dr is then

$$R = 2\pi r\rho/dr \tag{9}$$

and the eddy current density K_o will equal

$$K_o = V_o/2\pi r\rho \tag{10}$$

From equations 6, 7, and 8, one obtains for K_o

$$K_o = -j4\pi^2 10^{-9}(\mu f/\rho)(I_o n)r \tag{11}$$

Finally, the I^2R heat generated by induction is, per cubic centimeter,

$$W_o = K_o^2\rho/2 = 8\pi^4 10^{-18}(\mu^2 f^2/\rho) \times (I_o n)^2 r^2 \tag{12}$$

where W_o is average value and K_o is peak value.

At this point it is worthwhile to pause for a moment in the further development and to focus our attention on the interpretation of equations 11 and 12. It will be recognized that the generated heat is controlled by the ampere-turns and frequency of the inductor current, by the electrical resistivity and magnetic permeability[3] of the charge, and furthermore by the distance from the axis. The permeability of a number of ferromagnetic materials varies with the magnetic intensity and with the temperature. When the temperature of the charge has reached the Curie point, the permeability drops to unity with an attendant drop in heat generation.

A further inspection of equations 11 and 12 reveals the important facts that the density of the eddy currents K_o is zero at the center of the charge and increases as a linear function of the radius toward the surface (Figure 3). Since the rate of heat generation W_o per unit volume of the charge is proportional to the square of the current density (equation 12), it is obvious that the rate of heating W_o is also zero at the center of the charge, but increases with the square of the radius toward the surface of the charge. The greatest concentration of heat generation thus occurs in the surface layer (Figure 3). This concentration of heat generation toward the surface makes induction heating suitable for surface hardening applications. Although most of the heat is generated in the surface layer, the entire body of the charge can be heated if so desired; this is done simply by continued application of power, the heat being conducted thermally to the interior.

Such, briefly sketched, are the conclusions reached from an inspection of equations 11 and 12. These equations were obtained by disregarding the effect of mutual inductance. The validity of the conclusions, therefore, has to be limited to the region in which the effect of mutual inductance remains negligible. It is the object of the following to demarcate this region and to investigate what modifications the foregoing conclusions have to undergo when the effect of mutual inductance becomes pronounced.

Eddy currents K_o flowing in the charge create a magnetic flux Φ_1, which is interlinked with the sleeves and with the inductor. The flux Φ_1 is a function of the magnetic intensity H_1 which follows from Ampere's law

$$\oint_l H_1 dl = 0.4\pi \int\int_s K_o ds \tag{13}$$

Remembering that H_1 has no radial component and equals zero at the outside of the charge, the line integral on the left hand side of equation 13 simplifies for a slice of the height of one centimeter to H_1 (Figure 4). The surface integral on the right hand side also simplifies somewhat, resulting in

$$H_1 = 0.4\pi \int_r^a K_o dr \tag{14}$$

Simplifying the expressions for K_o by introducing a new parameter p, where

$$p = \frac{1}{2\pi}\sqrt{\frac{\rho 10^9}{2\mu f}} \tag{15}$$

one obtains

$$K_o = -j(1/2p^2)(I_o n)r \tag{16}$$

Substituting equation 16 into equation 14 and integrating, one obtains finally

$$H_1 = (-j\alpha^2/8p^2)\cdot 0.8\pi(I_o n)[1-(r/a)^2] \tag{17}$$

The radial distribution of H_1 is parabolic. The induction B_1 follows as

$$B_1 = \mu H_1 \tag{18}$$

and is shown in Figure 5.

The magnetic flux Φ_1 will be obtained from

$$\Phi_1 = \int_0^r B_1 \cdot 2\pi r \cdot dr \tag{19}$$

The following method of splitting the induction B_1 into two components $B_{1,m}$ and $B_{1,a}$ will greatly simplify the further analysis:

$$B_1 = B_{1,m} + B_{1,a} \tag{20}$$

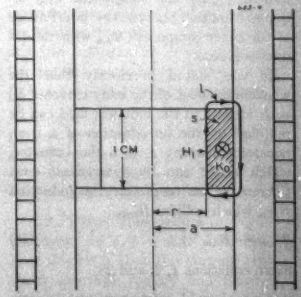

Figure 4. Sectional view of slice for illustration of Ampere's circuital law

Component $B_{1,a}$ shall have such radial distribution that the resulting flux $\Phi_{1,a}$ is not interlinked with the inductor:

$$\Phi_{1,a}\Big|_0^a = \int_0^a B_{1,a} \cdot 2\pi r \cdot dr = 0 \tag{21}$$

Integrating equation 20 and substituting from equation 21, one obtains an integral equation for $B_{1,m}$:

$$\int_0^a B_1 \cdot 2\pi r \cdot dr = \int_0^a B_{1,m} \cdot 2\pi r \cdot dr \tag{22}$$

The simplest radial distribution which can be assigned to $B_{1,m}$ is to be constant:

$$B_{1,m} = \text{constant} \tag{23}$$

Applying equation 23 to equation 22, we have

$$\int_0^a B_1 \cdot 2\pi r \cdot dr = B_{1,m} \int_0^a 2\pi r \cdot dr \tag{24}$$

and

$$B_{1,m} = \frac{1}{a^2\pi} \int_0^a B_1 \cdot 2\pi r \cdot dr \tag{25}$$

Utilizing equations 17 and 18, the integration of equation 25 results in

$$B_{1,m} = (-ja^2/8p^2) \cdot 0.4\pi\mu(I_o n) \tag{26}$$

The other component $B_{1,a}$ follows from equations 17, 18, 20, and 26:

$$B_{1,a} = (-ja^2/8p^2) \cdot 0.4\pi\mu(I_o n) \times [1-2(r/a)^2] \tag{27}$$

Both components $B_{1,m}$ and $B_{1,a}$, whose radial distributions are illustrated in Figure 5, form together the flux Φ_1. This flux therefore can be considered as consisting of two components: $\Phi_{1,m}$, which has a constant density $B_{1,m}$ throughout the charge, and $\Phi_{1,a}$, which is not interlinked with the inductor.

When considering the effect of the eddy currents K_o and hence of flux Φ_1 on the inductor, only the component $\Phi_{1,m}$ requires attention because the interlinkage of the other component $\Phi_{1,a}$ with the inductor is zero.

It was stated previously that the weakening effect of the eddy currents K_o with respect to the inductor field can be nullified by the introduction of a compensating current I_1 into the inductor, which easily can be determined now. Current I_1 has to produce an induction $B'_{1,m}$ which nullifies $B_{1,m}$.

$$B'_{1,m} = -B_{1,m} \tag{28}$$

From equations 1, 2, and 28,

$$0.4\pi\mu(I_1 n) = B'_{1,m} = -B_{1,m} \tag{29}$$

Applying equation 26, one obtains for the compensating current I_1 in the inductor

$$I_1 = -(-ja^2/8p^2)I_o \tag{30}$$

If this current I_1 is added to the original inductor current I_o, as it will be assumed, the magnetic action of the eddy currents K_o, as far as flux $\Phi_{1,m}$ is concerned, is completely cancelled. After the introduction of current I_1, the flux $\Phi_{1,m}$ ceases to exist and hence does not require any further attention. The only modification of the original eddy current

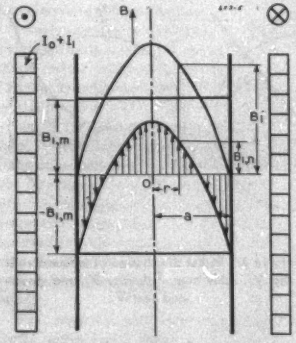

Figure 5. Longitudinal section, illustrating the distribution of induction B_i caused by eddy currents K_o

distribution as expressed in equations 11 and 12 will be caused by induction $B_{1,a}$ (Figure 5).

In addition to cancelling part of the eddy current field, current I_1 reflects into the inductor the I^2R loss, which occurs in the charge caused by the eddy currents K_o. The current I_1 is in phase with the voltage E_o and thus expresses true power consumption by the inductor (Figure 6). It can be proved that this power P_o expressed in terms of I_1 and E_o (equations 8 and 30) equals the energy dissipated in the charge by the eddy current K_o (equations 11 and 12):

$$P_o = E_o I_1/2 = \pi(a/2p)^4 \rho(I_o n)^2 = \int_0^a (K_o^2 \rho/2) \cdot 2\pi r \cdot dr \tag{31}$$

Returning to induction $B_{1,a}$, the corresponding flux $\Phi_{1,a}$ follows in analogy to equation 3:

$$\Phi_{1,a} = \int_0^a B_{1,a} \cdot 2\pi r \cdot dr \tag{32}$$

The induced voltage V_1 in the charge, caused by flux $\Phi_{1,a}$, is

$$V_1 = -j\omega\Phi_{1,a}10^{-8} \tag{33}$$

Substituting from equations 27 and 32, one obtains

$$V_1 = [(-ja^2/p^2)\pi\rho(I_o n)r^2/a^2] \times [(-ja^2/8p^2)(1-r^2/a^2)] \tag{34}$$

These voltages V_1 are induced in the charge by the flux $\Phi_{1,a}$ and previously have been disregarded after compensating voltages were introduced. Actually such compensating voltages do not exist and hence the voltages V_1 will be acting on the charge. Summarizing the reasoning thus far, it can be stated that the inductor carries the currents I_o and I_1, while the charge carries the eddy currents K_o. In addition, free residual voltages V_1 exist in the charge.

At this point an examination of the relative magnitudes of V_1 with respect to V_o is in order. Since the voltages V_1 will cause the flow of eddy currents K_1, just as V_o caused the flow of the eddy currents K_o, the relative magnitude of V_1 with respect to V_o will indicate whether the expression for the heat generation in the charge (equation 31) is sufficiently accurate or whether the effect of the voltages V_1 has to be taken into account.

Recasting the expression for V_o by using equations 6 and 15,

$$E_o = (-ja^2/p^2)\pi\rho(I_o n)r^2/a^2 \tag{35}$$

The ratio V_1/V_o becomes (equations 34 and 35)

$$V_1/V_o = (-ja^2/8p^2)(1-r^2/a^2) \tag{36}$$

For a ratio of $a/p < 1$, the ratio of the voltages V_1/V_o, and consequently of the eddy currents K_1/K_o, becomes small. Since the generated heat is proportional to K_o^2, and respectively K_1^2, the heat generated by the eddy currents K_1 is then negligible with respect to the heat generated by the eddy currents K_o, and the expression for the heat generation (equation 31) applies.

The current I in the inductor is

$$I = I_o + I_1 = I_o[1 + j(a^2/8p^2)] \tag{37}$$

Solving for I_o,

$$I_o^2 = I^2/[1 + j(a^2/8p^2)]^2 \tag{38}$$

Introducing I_o^2 into equation 31 and remembering that equation 31 is valid only for $a/p < 1$, I_o^2 can be approximated very closely by the inductor current I. Since the effective value of the inductor current

$$I_{eff} = I/\sqrt{2} \tag{39}$$

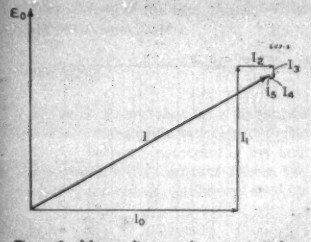

Figure 6. Vector diagram of currents in inductor

the heat generated in the charge can now be expressed as follows:

$$P_2 = 2\pi(a/2\rho)^4 \rho (I_0 n)^2 \quad \text{for } a/\rho \leq 1 \tag{40}$$

If, however, $a/\rho > 1$, the effect of V_1 has to be investigated. Just as the voltage V_0 produces the eddy current K_0, the voltage V_1 produces a new eddy current K_1, as fully explained in Appendix I. The effect of the eddy currents K_1 can be resolved in an additional current I_2 in the inductor (Figure 6) and free voltages V_2 as follows:

$$K_1 = \left(-j\frac{a^2}{8\rho^2}\right)^2 \frac{4}{a}(I_0 n)\frac{r}{a}\left(1 - \frac{r^2}{a^2}\right) \tag{42}$$

$$I_2 = -\left(-j\frac{a^2}{8\rho^2}\right)^2 I_0 \cdot \frac{1}{3} \tag{50}$$

$$V_2 = \left(-j\frac{a^2}{8\rho^2}\right) V_1 \left(\frac{2}{3} - \frac{r^2}{3a^2}\right) \tag{53}$$

Thus the current in the inductor consists of the vector sum of I_0, I_1, I_2, while the eddy currents consist of the vector sum of K_0, K_1. In addition, free residual voltages V_2 exist in the charge.

With the new eddy currents K_2 (in analogy to equation 42),

$$K_2 = \left(-j\frac{a^2}{8\rho^2}\right)^2 K_0 \left(-\frac{2}{3} + \frac{r^2}{a^2} - \frac{r^4}{3a^4}\right) \tag{54}$$

flowing in the charge, it can be seen that

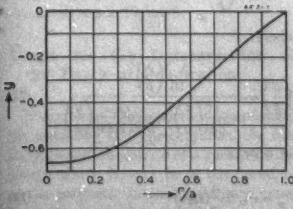

Figure 7. Function y indicates the progressive reduction of eddy current density toward the axis of charge

K_2 is in counterphase with eddy currents K_0, and hence K_2 can be algebraically subtracted from K_0 in order to obtain the total nonquadrature eddy current thus far derived. The charge also carries the eddy current K_1. This current K_1 is, however, in phase quadrature with K_0, and its effect on K_0 will be neglected for reasons of simplicity. Under this assumption K_2 expresses the amount by which the original intensity K_0 of the eddy currents (equation 16) will be modified if the voltages V_1 and V_2 are not negligible.

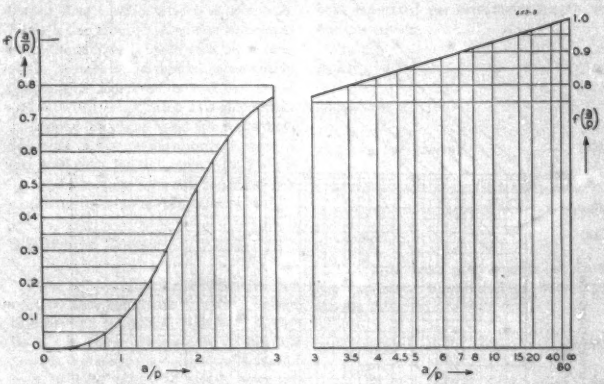

Figure 8. Graph for $f(a/\rho)$ (from equations 71 and 81)

In order to compare the new eddy current K_2 with the original eddy current K_0, the first is expressed in terms of the latter as shown in equation 55:

$$K_2/K_0 = \left(-j\frac{a^2}{8\rho^2}\right)^2 \left(-\frac{2}{3} + \frac{r^2}{a^2} - \frac{r^4}{3a^4}\right) = y \tag{55}$$

Aside from the term $(-ja^2/8\rho^2)^2$, the new eddy current K_2 equals the original eddy current K_0 times a function y. For better illustration, the function y is plotted in Figure 7. This figure reveals:

1. In the interior of the charge the new eddy current K_2 is opposed to the original eddy current K_0 at every point, resulting in a smaller eddy current density than expressed in equation 16, and therefore resulting in less heat generation than expressed in equation 12.

2. The eddy current density, and hence heat generation, is progressively reduced toward the center of the charge.

3. The relative reduction of eddy current density and heat generation in the interior is a function of the ratio a/ρ.

As pointed out in the preceding paragraphs, the generated heat decreases toward the axis at a higher rate than expressed by equation 12. The result is a preponderance of heat generation in the surface layer, called the skin of the charge which effect is called skin effect. If the ratio a/ρ is increased, the reduction of heat generation toward the axis of the charge is intensified resulting in a still greater preponderance of heat generation in the surface layer of the charge. Besides frequency, resistivity, and permeability, the radius a of the charge is an additional controlling factor for the skin effect. The skin effect may be produced equally in the case of a higher frequency and a charge of smaller diameter, as in the case of a lower frequency and a charge of larger diameter.

After this discussion of skin effect, the attack on the main problem, namely the computation of heat generation, will be resumed. The eddy currents K_2 lead to magnetic intensities H_2 which, in turn, are resolved in a current I_2 in the inductor and free voltages V_2 in the charge. If this method is repeated, further currents I_4, I_6, I_8 are obtained for the inductor:

$$I_1 = -(-ja^2/8\rho^2)I_0 \tag{30}$$

$$I_3 = -(-ja^2/8\rho^2)^2 I_0 \cdot 1/3 \tag{50}$$

$$I_5 = -(-ja^2/8\rho^2)^3 I_0 \cdot 1/3 \tag{56}$$

$$I_7 = -(-ja^2/8\rho^2)^4 I_0 \cdot 4/_{99} \tag{57}$$

$$I_9 = -(-ja^2/8\rho^2)^5 I_0 \cdot 14/_{315} \tag{58}$$

The current components in Figure 6 are shown for $a/\rho = 2.4$. It is evident from Figure 6 that the current components converge rapidly and hence the current represented by I is a very close approximation for the actual current in the inductor. For decreasing ratios of

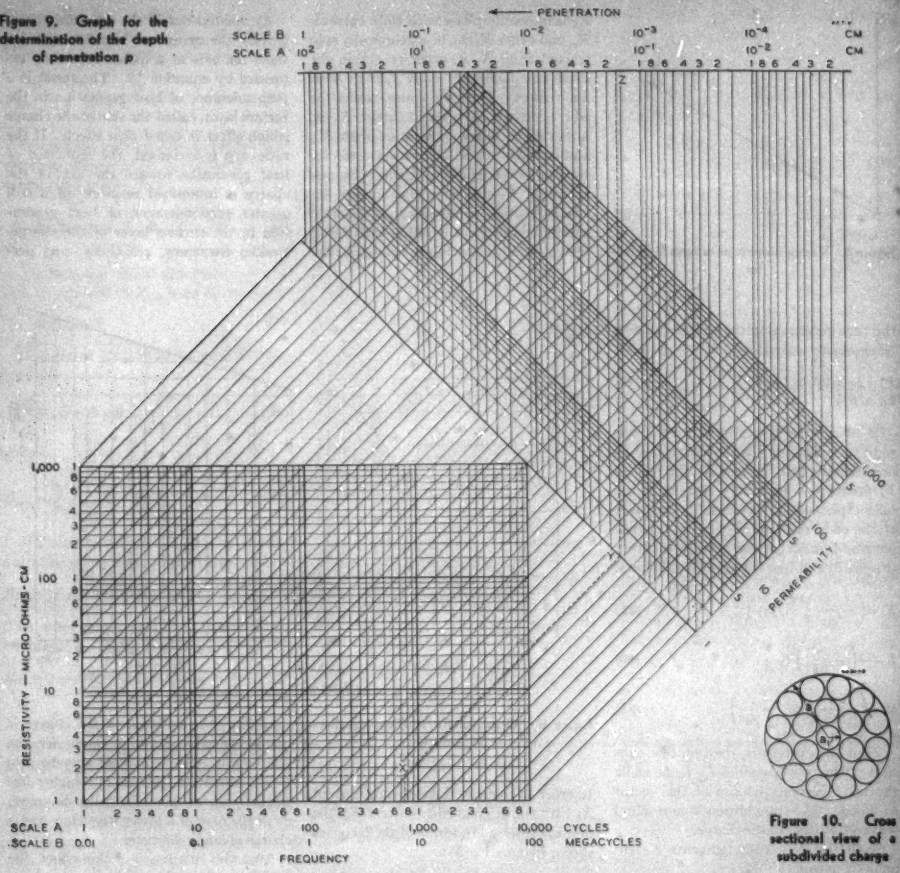

Figure 9. Graph for the determination of the depth of penetration p

Figure 10. Cross sectional view of a subdivided charge

a/p, the convergence is more rapid yet and hence the approximation is still closer.

When the true components I_1, I_2, I_3 are multiplied with the inductor voltage E_0, the true power P dissipated in the charge is obtained. This is shown in Appendix II, resulting in

$$P = 2\pi p \frac{\frac{1}{16}\left(\frac{a}{p}\right)^4}{1+\frac{11}{384}\left(\frac{a}{p}\right)^4-\frac{77}{2{,}211{,}840}\left(\frac{a}{p}\right)^8}(I_{eff})^2$$

for $a/p<3$ (69)

Thus the generated heat has been determined in the form of a series, as a function of radius, resistivity, permeability of the charge, and the ampere-turns and frequency of the inductor current. For $a/p = 3$ the accuracy of the series is within 1.1 per cent. For smaller ratios of a/p the error rapidly approaches zero. The convergence of the series is so rapid that for a ratio of $a/p \lesssim 2.2$, the third term in the denominator of equation 69 can be neglected without introducing an error of more than 1.2 per cent. The remaining series is still very rapidly converging for decreasing ratios of a/p. If $a/p = 0.8$, the second term in the denominator can be neglected without causing an error of more than 1.2 per cent, which error rapidly decreases for decreasing ratios of a/p.

The formulation of generated heat by means of a sharply converging series introduces a new tool for the analytical attack of various theoretical problems. For practical rapid determination of the heat, equation 60 is split into 2 parts:

$$P = P_\infty \cdot f\left(\frac{a}{p}\right) \tag{70}$$

where

$$f\left(\frac{a}{p}\right) = \frac{\frac{\sqrt{2}}{16}\left(\frac{a}{p}\right)^3}{1+\frac{11}{384}\left(\frac{a}{p}\right)^4-\frac{77}{2{,}211{,}840}\left(\frac{a}{p}\right)^8} \tag{71}$$

for $a/p<3$

$$P_\infty = \pi\sqrt{2}p\frac{a}{p}(I_{eff})^2 \tag{72}$$

While function $f\ (a/p)$ is plotted in Figure 8, a graph shown in Figure 9, and

explained later in the text, facilitates the rapid determination of p.

Case $a/p \geq 3$

It can be shown[3] that for a magnitude of p which is negligible with respect to the radius a, the heat generation W per unit volume at a radial distance d from the surface of the charge, can be expressed by

$$W = \frac{1}{2}\left(\frac{In}{p}\right)^2 \rho\epsilon \frac{-d\sqrt{2}}{p} \tag{73}$$

where

$$d = a - r \tag{74}$$

The heat generated in a slice of one centimeter height is

$$P = \int_0^a W \cdot 2\pi r \cdot dr \tag{75}$$

If this integral is evaluated as shown in Appendix III, the following expression for the generated heat is obtained as follows:

$$P = \pi\sqrt{2}\rho\frac{a}{p}\left(1 - \frac{1}{\frac{a\sqrt{2}}{p}}\right)(I_{eff}n)^2 \tag{80}$$

for $a/p \geq 3$

Equation 80 is accurate within 0.1 per cent for $a/p = 3$. For larger ratios of a/p, the error rapidly approaches zero.

It will be recognized that the application of equation 72 leads to

$$P = P_\infty \cdot f\left(\frac{a}{p}\right) \tag{70}$$

where

$$f\left(\frac{a}{p}\right) = 1 - \frac{1}{\frac{a\sqrt{2}}{p}} \tag{81}$$

for $a/p \geq 3$

and

$$P_\infty = \pi\sqrt{2}\rho\frac{a}{p}(I_{eff}n)^2 \tag{72}$$

The function $f(a/p)$ (equation 81) can be plotted very rapidly as a straight line, using a hyperbolic scale for the abscissa axis, as shown in Figure 8.

Graph for the Determination of the Depth of Penetration

Every one of the important equations in the preceding analysis contained the factor p (equation 15). For a radius of the charge which is very large compared to p, the magnetic intensity declines exponentially from the surface toward the interior of the charge.[4] At a distance of $p\sqrt{2}$ from the surface, the magnetic intensity and hence the eddy currents are $1/e$ of their respective values at the surface. The decay of the magnetic intensity as a function of its penetration into the charge can thus be expressed in terms of p, and hence p is often referred to as depth of the magnetic field penetration.

For rapid determination of p, the graph in Figure 9 is recommended. Suppose the penetration should be determined for copper at room temperature ($\rho = 1.7 \cdot 10^{-6}$ ohm-centimeters, $\mu = 1$) and a frequency of 750 cycles. Erect verticals on the frequency and resistivity axes at the required points, as shown by dotted lines, and intersect at point X. Draw a line through X under 45 degrees until intersection is made with the permeability system at the desired permeability (point Y). Erect a vertical line on Y and intersect penetration axis at point Z. If scale A has been used for frequency, use scale A for penetration; if scale B has been used for frequency, use scale B for penetration. For the foregoing example the solution is 0.17 centimeter.

Subdivided Charge

Thus far the charge consisted of one cylinder with the radius a. When induction heating is applied to melting operations, the charge with which the heating process is started may consist of a multitude of solid pieces of metal, so-called scrap whose upper range of size is limited by the inside diameter of the crucible. As far as the geometry of the crucible is concerned, there is no lower limit for the size of the scrap. It has been observed, however, that the time for melting the same weight of scrap depends upon the size of the scrap, other conditions such as magnitude and frequency of the inductor current remaining the same. Under these assumptions the energy spent on copper losses in the inductor is merely a function of the time during which the current is applied. If various sizes of scrap require various amounts of time for melting, although the weight of scrap remains the same, it is obvious that the size of the scrap influences the efficiency of heating.

In order to analyze the effect of scrap size, it will be assumed that the charge consists of a number of solid, identical, round bars which fill the interior of the crucible as shown in Figure 10. Singling out one bar with the radius a_1, the generated heat can be computed, as previously shown in equation 70, substituting a_1 for a. Since the charge, in this case the bar, does not create a magnetic field outside its contours, the space around the bar remains at the same magnetic intensity whether the bar is present or not. This means that the state within one bar is unaffected by the presence of other bars within the same inductor. If, however, the bars touch each other, a current can be transferred across the common surface making the bars interdependent. It will be assumed in the following that the bars do not touch each other, or that oxides are present at the surface of the bars which are sufficiently insulating to make the current transfer betwen bars negligible.

As in the preceding (equation 70), the heat generated per centimeter length of one bar equals

$$P_1 = P_{\infty 1} \cdot f\left(\frac{a_1}{p}\right) \tag{82}$$

where

$$P_{\infty 1} = \pi\sqrt{2}\rho\frac{a_1}{p}(I_{eff1} \cdot n)^2 \tag{83}$$

If the number of rods is i, the total area A of the cross sections of the rods equals

$$A = ia_1^2\pi \tag{84}$$

The total heat generated in all bars per centimeter length follows from Appendix IV:

$$P = A \cdot (\mu f 10^{-9}) \cdot \varphi\left(\frac{a_1}{p}\right) \cdot (I_{eff}n)^2 \tag{90}$$

The function of $\varphi(a_1/p)$ (equations 88 and 89) has been plotted in the graph, as shown in Figure 11. The most striking feature of the function is its maximum. It means that for a certain ratio of a_1/p, the generated heat is a maximum. Since the magnitude and frequency of the current in the inductor are assumed constant, the losses in the inductor are also constant, and hence maximum heat generation means maximum efficiency. In order to find the maximum, the conventional approach of differentiating function $\varphi(a_1/p)$ (equation 88) is applied. The solution is

$$\left[\varphi\left(\frac{a_1}{p}\right)\right]_{max} = 29.86 \tag{91}$$

for $a_1 = 2.53p$

For a given material and frequency, there is one certain radius at which maximum heat generation is achieved. It should, however, be borne in mind, that most metals increase their resistivity with increasing temperature. The penetration p at lower temperature is smaller (equation 15) than at higher temperature. If the radius $a_1 = 2.53\ p$ has been determined for the low temperature, the heat generation will be at maximum at

the outset of heating. As the heating process goes on, the temperature of the charge will rise and its resistivity increases. The factor p will also increase, resulting in a decreasing (a_i/p). It is obvious from Figure 11 that a reduction of heat generation will occur. The thermal losses of the charge, however, increase with the temperature, while the generated heat decreases. It is therefore possible that a temperature equilibrium establishes itself below the desired temperature.

In order to avoid this limitation of temperature, the radius a_i of the charge has to be computed from a penetration p, which is based on a resistivity of higher value than at room temperature. If p is based on the resistivity of the metal at its highest temperature, the generated heat also will reach its maximum at the highest temperature.

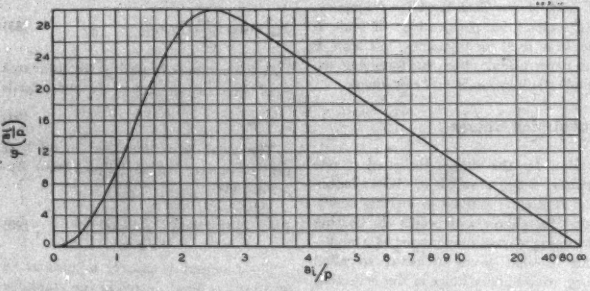

Figure 11. Graph for $\varphi(a_i/p)$ (from equations 88 and 89)

The maximum heat generation follows from equations 90 and 91:

$$P_{max} = 29.86A\,(\mu/10^{-9})(I_{eff}n)^2 \qquad (92)$$

From the point of view of efficiency of induction heating, equation 92 is very significant. If the charge is not subdivided, and provided $a \gg p$, the generated heat P is given by equation 70. The heat generation P is proportional to the radius of the charge, and the copper losses in the inductor are in proportion to the radius of the inductor. If the radius of the charge is increased, the radius of the inductor has to be increased by a proportional amount. The result is that the ratio between heat generation and inductor loss remains constant, which in turn means that the efficiency is limited to a constant amount depending on the resistivity and permeability of the charge.

For a subdivided charge no such limitation exists. While the loss in the inductor increases linearly with its radius, the area A of the total cross-section of the bars increases approximately with the square of the radius. The result is that by increasing the radius of the inductor, the heat generation in the charge increases much faster than the losses in the inductor, hence the efficiency approaches asymptotically 100 per cent.

Appendix I

The voltage V_1 will cause the flow of new eddy currents of the density K_1. The magnitude and phase of these new eddy currents is controlled by V_1, the resistance of the sleeves, and the voltages V_2 induced in the sleeves by the eddy currents K_1 caused by mutual reactance. A compensating current I_3 is introduced in the inductor to counteract the weakening action of the eddy currents K_1. Furthermore, a compensating voltage $-V_1$ is introduced in series with each sleeve, developing a voltage equal in magnitude and opposite in sign with respect to the voltage induced in the sleeve by the eddy currents K_1 in the charge, and the compensating current I_3 in the inductor, thus nullifying the voltages of mutual reactance. The eddy current K_1 is now only a function of V_1 and the resistance of the sleeve (equation 10):

$$K_1 = E_1/2r\pi\rho \qquad (41)$$

Taking V_1 from equation 34, one obtains

$$K_1 = \left(-j\frac{a^3}{8\rho^3}\right)^2 \frac{4}{a}(I_e n)\frac{r}{a}\left(1-\frac{r^2}{a^2}\right) \qquad (42)$$

The magnetic intensity H_1 results in analogy to equation 14:

$$H_1 = 0.4\pi \int_r^a K_1 dr \qquad (43)$$

and integrating equation 42,

$$H_1 = \left(-j\frac{a^3}{8\rho^3}\right)^2 \cdot 0.4\pi(I_e n)\left(1-2\frac{r^2}{a^2}+\frac{r^4}{a^4}\right) \qquad (44)$$

Again, the resulting induction B_1 is split into two components similar to equation 20:

$$B_1 = B_{1,m} + B_{1,a} \qquad (45)$$

Stipulating the same requirements for $B_{1,m}$ and $B_{1,a}$, as previously for $B_{1,m}$ and $B_{1,a}$, respectively,

$$B_{1m} = \left(-j\frac{a^3}{8\rho^3}\right)^2 \cdot 0.4\pi\mu(I_e n)\cdot\frac{1}{3} \qquad (46)$$

The other component $B_{1,a}$ follows from equations 44 and 46:

$$B_{1,a} = \left(-j\frac{a^3}{8\rho^3}\right)^2 \cdot 0.4\pi\mu(I_e n)\left(\frac{2}{3}-2\frac{r^2}{a^2}+\frac{r^4}{a^4}\right) \qquad (47)$$

In order to cancel the effect of $B_{1,m}$, a compensating current I_3 has to flow through the inductor which produces an induction

$$B'_{1,m} = -B_{1,m} \qquad (48)$$

From equations 1, 2, and 48

$$0.4\pi\mu(I_3 n) = B'_{1,m} = -B_{1,m} \qquad (49)$$

Applying equation 46 one obtains the compensating current I_3:

$$I_3 = -\left(-j\frac{a^3}{8\rho^3}\right)^2 I_e \cdot \frac{1}{3} \qquad (50)$$

Only the component $B_{2,a}$ can be effective in inducing voltages V_2 in the sleeves. The corresponding flux

$$\Phi_{2,a} = \int_r B_{2,a} \cdot 2r\pi \cdot dr \qquad (51)$$

which, in turn, induces voltages V_2 in the charge

$$V_2 = -j\omega\Phi_{2,a}10^{-8} \qquad (52)$$

Substituting for $\Phi_{2,a}$ in equation 52 results in an expression for V_2 as follows:

$$V_2 = \left(-j\frac{a^3}{8\rho^3}\right) V_1 \left(\frac{2}{3}-\frac{r^2}{3a^2}\right) \qquad (53)$$

Appendix II

The inductor current I has two components: the resistive component I_R in phase with the voltage E_e and the inductive component I_x lagging 90 degrees behind.

$$I = I_R + I_x \qquad (59)$$

The resistive component I_R follows from

$$I_R = I_1 + I_3 + I_5 \qquad (60)$$

and the inductive component I_x equals

$$I_x = I_e + I_3 + I_4 \qquad (61)$$

The resistive component I_R follows from equations 30, 56, 58, and 60:

$$I_R = jI_e\left\{\frac{a^3}{8\rho^3}\left[1-\frac{1}{6}\left(\frac{a^3}{8\rho^3}\right)^2 + \frac{13}{270}\left(\frac{a^3}{8\rho^3}\right)^4\right]\right\} \qquad (62)$$

and the inductive component follows from equations 50, 57, and 61

$$I_s = I_o\left[1+\frac{1}{3}\left(\frac{a^2}{8p^2}\right)^2-\frac{4}{45}\left(\frac{a^2}{8p^2}\right)^4\right] \quad (63)$$

The absolute value of the inductor current I (equation 59) is

$$I=\sqrt{I_R^2+I_s^2} \quad (64)$$

Substituting for equations 62 and 63 in equation 64 and neglecting terms of sixth power and up, one obtains for the current I

$$I=I_o\sqrt{1+\frac{5}{3}\left(\frac{a^2}{8p^2}\right)^2-\frac{2}{5}\left(\frac{a^2}{8p^2}\right)^4+\ldots} \quad (65)$$

The heat generated by eddy currents is taken from the line in the form of the resistive component I_R of inductor current I. The average value of generated heat therefore can be expressed as

$$P=E_oI_R/2 \quad (66)$$

where E_o and I_R are peak values.

The resistive component I_R is obtained from equations 62 and 65:

$$I_R=I\left(\frac{a^2}{8p^2}\right)\cdot\frac{1-\frac{1}{6}\left(\frac{a^2}{8p^2}\right)^2+\frac{13}{270}\left(\frac{a^2}{8p^2}\right)^4}{\sqrt{1+\frac{5}{3}\left(\frac{a^2}{8p^2}\right)^2-\frac{2}{5}\left(\frac{a^2}{8p^2}\right)^4}} \quad (67)$$

This expression can be used in equation 66, and by further reference to equations 8 and 67 one obtains for the average power

$$P=4\pi\rho\left(\frac{a^2}{8p^2}\right)^2\times\frac{1-\frac{1}{6}\left(\frac{a^2}{8p^2}\right)^2+\frac{13}{270}\left(\frac{a^2}{8p^2}\right)^4}{1+\frac{5}{3}\left(\frac{a^2}{8p^2}\right)^2-\frac{2}{5}\left(\frac{a^2}{8p^2}\right)^4}(In)^2 \quad (68)$$

Dividing the denominator by the numerator and neglecting terms of sixth and higher powers, equation 68 simplifies to

$$P=2\pi\rho\,\frac{\frac{1}{16}\left(\frac{a}{p}\right)^4}{1+\frac{11}{384}\left(\frac{a}{p}\right)^4-\frac{77}{2{,}211{,}840}\left(\frac{a}{p}\right)^8}(In)^2 \quad (69)$$

for $a/p<3$

Appendix III

Applying the expression for W (equation 73) to equation 75 and integrating between the limits $r=0$ and $r=a$ results in the following operations:

$$P=\frac{1}{2}\left(\frac{In}{p}\right)^2\rho 2\pi\int_o^a r\cdot\epsilon^{-\frac{(a-r)\sqrt{2}}{p}}\cdot dr$$

$$=\frac{1}{2}\left(\frac{In}{p}\right)\rho 2\pi\cdot\epsilon^{-\frac{a\sqrt{2}}{p}}\int_o^a r\cdot\epsilon^{\frac{r\sqrt{2}}{p}}\cdot dr \quad (76)$$

$$\int_o^a r\cdot\epsilon^{\frac{r\sqrt{2}}{p}}\cdot dr=\frac{p^2}{2}\left(\frac{r\sqrt{2}}{p}-1\right)\epsilon^{\frac{r\sqrt{2}}{p}}\Big|_o^a$$

$$=\frac{p^2}{2}\left[\left(\frac{a\sqrt{2}}{p}-1\right)\epsilon^{\frac{a\sqrt{2}}{p}}+1\right] \quad (77)$$

Using the results of equation 77 in equation 76 leads to

$$P=\frac{1}{2}\left(\frac{In}{p}\right)^2 2\pi\rho\,\frac{p^2}{2}\left(\frac{a\sqrt{2}}{p}-1+\epsilon^{-\frac{a\sqrt{2}}{p}}\right) \quad (78)$$

$$\epsilon^{-\frac{a\sqrt{2}}{p}}\ll\frac{a\sqrt{2}}{p}-1 \qquad \text{for } a/p\geq 3 \quad (79)$$

The exponential term in equation 78 thus can be neglected and the generated heat per one centimeter height of the charge is

$$P=\pi\sqrt{2}\rho\,\frac{a}{p}\left(1-\frac{1}{\frac{a\sqrt{2}}{p}}\right)(I_{eff}n)^2 \quad (80)$$

for $a/p\geq 3$

Appendix IV

From equations 70, 82, 83, and 84,

$$P=A\sqrt{2}\,\frac{1}{a_1p}\cdot\rho\cdot f\left(\frac{a_1}{p}\right)(I_{eff}n)^2 \quad (85)$$

Recasting equation 85 and substituting from equation 15 for p,

$$P=A\sqrt{2}\cdot 8\pi^2(\mu f10^{-9}/\rho)\times\left\{\left[f\left(\frac{a_1}{p}\right)\right]\Big/\left(\frac{a_1}{p}\right)\right\}(I_{eff}n)^2 \quad (86)$$

Introducing

$$\varphi\left(\frac{a_1}{p}\right)=8\pi^2\sqrt{2}\left[f\left(\frac{a_1}{p}\right)\right]\Big/\frac{a_1}{p} \quad (87)$$

for $a_1/p<3$ the function $\varphi\left(\frac{a_1}{p}\right)$ follows from equation 71:

$$\varphi\left(\frac{a_1}{p}\right)=\pi^2\,\frac{\left(\frac{a_1}{p}\right)^2}{1+\frac{11}{384}\left(\frac{a_1}{p}\right)^4-\frac{77}{2{,}211{,}840}\left(\frac{a_1}{p}\right)^8}$$

$$a_1/p<3 \quad (88)$$

And for $a_1/p\geq 3$ the function $\varphi\left(\frac{a_1}{p}\right)$ follows from equation 81:

$$\varphi\left(\frac{a_1}{p}\right)=8\sqrt{2}\pi^2\left(1-\frac{1}{\frac{a_1\sqrt{2}}{p}}\right)\Big/\frac{a_1}{p} \quad (89)$$

$$\frac{a_1}{p}\geq 3$$

Returning to the heat generation it can be expressed as

$$P_{max}=29.86A(\mu f10^{-9})(I_{eff}n)^2 \quad (92)$$

Appendix V. Definitions of Symbols

A = total area of subdivided charge, in square centimeters

a = radius of nonsubdivided charge, centimeters

a_i = radius of bars in subdivided charge, centimeters

B = induction, peak value of sinusoid, gausses

d = distance of a point inside of charge to surface, centimeters

E = voltage, peak value of sinusoid, volts

f = frequency of inductor current, cycles per second

$f(a/p)$ = a function of (a/p)

H = magnetic intensity, peak value of sinusoid, oersteds

I = current, peak value of sinusoid, amperes

I_{eff} = current, rms value, amperes

i = number of bars in subdivided charge

$j=\sqrt{-1}$

K = current density of eddy currents, peak value of sinusoid, amperes per square centimeter

l = length of line over which integral is taken

n = number of turns of inductor per centimeter axial length

P = power, average value, watts

p = penetration, centimeters

s = surface over which integral is taken, square centimeters

t = time, seconds

V = induced voltage in charge, peak value of sinusoid, volts

W = generated heat, average value, watts per cubic centimeter

ϵ = base of natural logarithms, 2.71828

μ = permeability, unity

π = 3.14159

Φ = magnetic flux, peak value of sinusoid, maxwells

$\varphi(a_i/p)$ = a function of a_i/p

ρ = resistivity, ohm-centimeters

ω = angular velocity, radians per second

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Application of the Ohm and Mho Principles to Protective Relays

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THE mho relay unit was first used 15 years ago as the directional unit for an early-type reactance relay. Thus it can be said that "mho" applied to relays is a new term applied to an old principle. The mathematical justification for the term has been given in a paper[1] describing the use of the mho unit in a carrier-current relaying scheme. The mho unit in its present form is a directional impedance unit whose accuracy is comparable with that of the reactance ohm unit used in a distance relay.

The mho characteristic (Figure 1C) is suited ideally for protecting long or heavily loaded transmission lines because it is much less likely to trip on power swings than the conventional reactance or impedance relays. Another desirable feature is that a relay for phase faults should operate only on faults involving the phase pair with which the relay is associated; all other faults or system conditions should not affect it. In Figures 1A and 1B, the large tripping area of the impedance characteristics of the impedance and reactance relays shows that these relays are susceptible to power swings and faults in other phases (denoted by asterisks), whereas the snug fit of the mho circle around the fault area in Figure 1C indicates that the mho relay effectively prevents tripping for power swings and for any faults but those for which the relay is set to trip.

The fact that the mho unit combines sensitive directional action with accurate ohmic measurement means that one mho unit does what two conventional units did before. This not only eliminates the contact races that can occur between the directional element and the measuring element but obviously simplifies the circuits to which the relay is applied.

With these advantages it might appear that the mho unit should be used universally for all applications involving distance measurement. This is generally true, but there is a lower limit of impedance for which it can be set for reasons discussed later. Lines too short for the mho unit still must be protected by the reactance ohm unit.

Several new relays will be described, some of which use ohm units and mho units to perform existing relay functions more efficiently and others to perform some new functions. In order to understand the operation of these new relays, it may be helpful first to consider briefly their operation and to compare their pickup characteristics on the impedance diagram.

Relation Between Ohm and Mho Units

First of all, it should be understood that ohm units and mho units are merely refinements of the straight impedance relay. All distance relays measure the distance to a fault by comparing the current in the faulted circuit with the potential across it. In the impedance relay, this is done by opposing the torques of two electromagnets, one having a current winding and the other a potential winding (Figure 2A). The impedance measured by such a relay is not always a true measurement of distance, however. On short lines the additional potential drop in an arcing fault tends to prevent the impedance relay from operating, and on long lines, the current may be high enough under load or power swing conditions relative to the voltage to present to the relay an impedance as low as that of a fault and cause undesirable tripping.

This difficulty can be overcome largely by the use of the product-type relay whose torques are not proportional to current and voltage alone but to the products of I and E with a third quantity which, being common to both, does not affect the ratio balance E/I but provides phase-angle discrimination. This is shown schematically in Figures 2B and 2C.

The flux from the additional pair of poles (shown vertically in Figures 2B and 2C) acts in much the same way as the current or potential polarizing flux in a directional ground relay, and for want of a better name it will be referred to in the following as a polarizing flux.

The current polarizing flux in Figure 2B goes from the upper I pole through the induction cylinder and the central core iron stacking to the lower I pole and induces a current in the cylinder which flows perpendicular to the plane of the paper up and down the sides of the cup opposite the other two poles. The current opposite the operating pole I reacts with the flux from that pole to produce an I^2 torque tending to close the relay contacts, and the current in the cylinder near the E pole reacts with the flux from that pole producing an EI torque tending to keep the contact open.

In the following paragraphs, it will be shown that the provision of what we have called polarizing poles not only overcomes the above difficulties of distance measurement but provides some interesting new applications. Figure 3 shows the general construction of a high-speed product-type unit, the 4-pole induction cylinder unit.

Current Polarization (Ohm Units)

The torque is the product of the current polarizing flux times the fluxes from the opposed I and E poles. Hence the equation for the operating point, which determines the pickup characteristic, is

$$I[KI - E\cos(\phi - \theta)] = 0 \qquad (1)$$

where K is a winding constant, ϕ is the phase angle of the protected circuit, and θ is the angle of the relay characteristic.

Dividing through by I^2 and rearranging the terms, the equation becomes $Z\cos(\phi - \theta) = K$. Thus the current polarizing winding makes the relay respond to impedance only at a particular angle which is determined by the phase angle of the potential circuit of the relay. For example, a simple 4-pole induction cylinder unit with a current polarizing winding, reacting with a current operating pole and a potential restraining pole, operates on a component of impedance 20 degrees more leading than resistance. Such a relay (Figure 4) has been used as a blinder[2] for preventing other protective relays from tripping during very severe power swings. Two such ohm units, polarized in opposite directions, can be connected through auxiliary relays so as to detect an out-of-step condition after the first half swing period.

Adding a capacitor to make the potential circuit of the aforementioned unit at unity power-factor makes $\theta = 90$ degrees in the pickup equation, which becomes $(E/I)\sin\phi = K$ or $X = K$. In other words, the relay operates on reactance (Figure 5).

The reactance relay is used where the

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arc resistance is likely to be comparable with the impedance of the protected section and hence likely to interfere with the operation of the impedance relay. The reactance relay ignores the arc resistance and hence is indispensable for short lines and for protecting against ground faults.

Potential Polarization (Mho Units)

With potential polarization, the torque is the product of the potential-polarizing flux times the fluxes from the opposed I and E poles. Hence the equation for pickup is

$$E[I\cos(\phi-\theta)-K'E]=0 \qquad (2)$$

or $-K'E^2+EI\cos(\phi-\theta)=0$. Dividing through by E^2 and putting the K' term on the right, we get $Y\cos(\phi-\theta)=K'$, which is a straight line on an admittance diagram and thus represents a constant component of admittance, that is, the relay will pick up at a constant value of mhos at a certain angle and therefore has been called a mho unit. This is parallel to the case of the ohm unit which picks up at a constant component of impedance, as shown in the impedance diagram of Figure 4A.

It is generally more convenient to plot distance-relay characteristics on an impedance diagram. The impedance equation of the mho unit is obtained by putting the EI term on the right side of the equation and dividing through by $K'EI$, which gives $Z=(1/K')\cos(\phi-\theta)$.

This is the equation of a circle, of diameter $1/K'$, which passes through the origin (Figure 6A). The impedance characteristic of a mho relay is therefore a circle passing through the origin.

The fact that the characteristic passes through the origin means that the unit is inherently directional. The phase angle of the relay characteristic is the angle θ between the diameter of the impedance circle and the R axis. By making θ equal to or a little less lagging than ϕ, the phase angle of the line, the circle is made to fit very closely around the fault area so that the relay is less sensitive to power swings and hence valuable for the protection of long or heavily loaded lines.

Offset Mho Circle

Since both the terms of the equation of the mho relay contain E, it would appear that the relay has zero torque when the potential is zero, as for a bus fault. This shortcoming is avoided in an instantaneous mho relay by providing memory action in the polarizing circuit which maintains the relay polarizing voltage E_{pol} for a few cycles after the line voltage has disappeared, but does not affect the ohmic characteristic. This will be apparent from the torque equation

$$E_{pol}[I\cos(\phi-\theta)-K'E]=0 \qquad (3)$$

Memory action cannot be made to last long enough for the time-delay backup step, but the torque can be maintained in this case by adding torque caused by current alone. The functions of the third step of a distance relay are usually to start carrier blocking and to control the backup time-delay trip. Memory action is used to provide initially high torque to ensure starting carrier very promptly and the contacts are held closed after the expiry of the memory action by the current torque. The introduction of the current torque puts the KI^2 term back into the equation of the mho unit, thus making it the general equation

$$KI^2-K'E^2+EI\cos(\phi-\theta)=0$$

(See Appendix I.)

The offset is secured by adding to the

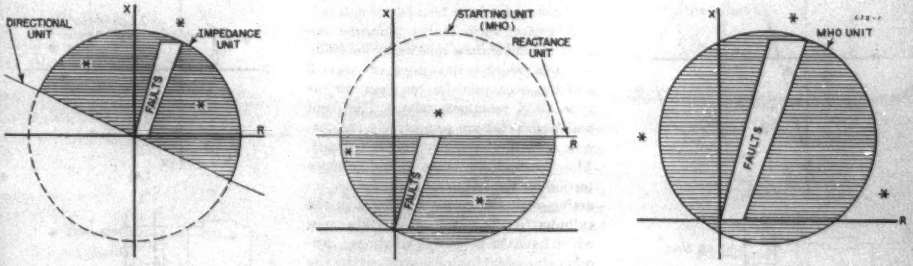


Figure 1. Tripping characteristics

A. Impedance unit
B. Reactance unit
C. Mho unit

The relays trip in the shaded area. Crosses are conditions for which tripping is undesirable

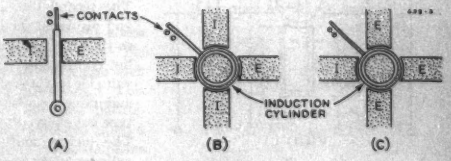


Figure 2. Schematic diagrams

A. Impedance unit
B. Ohm unit
C. Mho unit

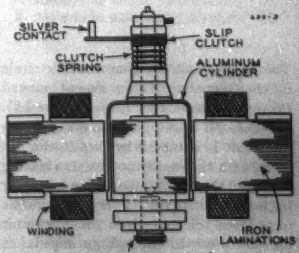


Figure 3. Schematic diagram of 4-pole induction cylinder unit

line potential a biasing potential, IZ_b, proportional to the current, which has the effect of moving the characteristic impedance circle bodily by an amount Z_b. Substituting $E+IZ_b$ for E in the equation for the mho relay, we get

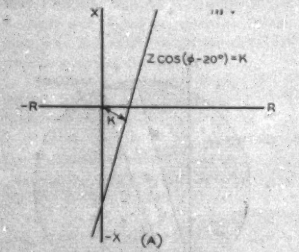
$$-K'(E+IZ_b)^2+(E+IZ_b)I\cos(\phi-\theta)=0 \quad (4)$$

Dividing through by I^2, the equation becomes

$$-K'(Z+Z_b)^2+(Z+Z_b)\cos(\phi-\theta)=0$$

or

$$Z=\frac{\cos(\phi-\theta)}{K'}-Z_b \quad (5)$$



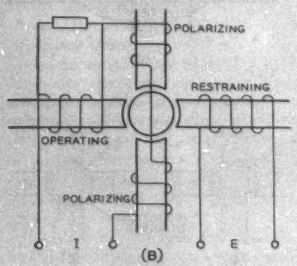


Figure 4

A. Characteristic of ohm unit (blinder)
B. Schematic connections of ohm unit

This shows that the characteristic circle is the same as before except moved through an impedance Z_b (see Figure 7A).

Figure 7B shows how the offset of the mho unit is obtained by introducing, in series with the supply potential, a biasing potential that is obtained from a reactor in the current circuit. Every point on the impedance characteristic of the unit thereby is moved through an impedance equal to that of the reactor. In order to reduce the burden imposed on the current transformers by the reactor, it is provided with two windings. The primary winding with few turns is in the current circuit, and the secondary winding with many turns is in the potential circuit. It is thus a contraction of a transformer and a reactor and is called a transactor.

This offset characteristic is particularly useful for out-of-step blocking because, with the opening of circuit breakers after a fault and hunting between two or more groups of machines, the impedance "seen by the relay" may approach the relay characteristic at almost any angle. Hence the only sure way of initiating out-of-step blocking is by a relay whose characteristic entirely sufrounds the characteristic of the tripping relay as shown in Figure 8A.

Relays Using Polarized Impedance Units

A typical form of the polarized impedance unit is the 4-pole induction cylinder unit, which is illustrated in Figure 3 and has been used for ten years in the type GCX reactance relay. The front and back poles are respectively the current operating and potential restraining. The fluxes from these poles produce torque on the induction cylinder by reacting with the currents induced in the cylinder by the flux from the side poles which have the polarizing windings. Another sinusoidal torque is produced by the flux from the polarizing poles reacting with the currents in the cylinder induced by the operating and restraining poles. The second torque is equal to the first and displaced 90 degrees from it in time so that the total torque is not sinusoidal but continuous. This is one of the most valuable features of the induction cylinder and induction disc units and is an advantage not enjoyed by any other relay units. The pickup and dropout of induction cylinder units are practically the same, and their characteristic circles are very close to geometrical perfection.

These units are available in three forms: the current polarized (ohm) unit, the potential polarized (mho) unit, and the offset mho unit in which the potential is biased from the current circuit. In the following paragraphs, uses of these units will be discussed.

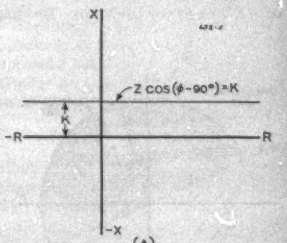
Applications of the Mho Unit

One-Step Distance Relay

The simplest application requires a single-step mho relay, type CEY, one per phase. The mho units trip instantaneously and are usually set to cover 90 per cent of the protected section. Backup protection for the neighborhood of the next bus can be provided by the mho type IBCV directional overcurrent relay to be described.

The instantaneous tripping zone provided by the single-step mho relay is superior to that of instantaneous overcurrent or single-step impedance protection because:

1. It is inherently directional, so that only a single contact appears between the battery and the trip coil, which is the ultimate in simplicity and reliability.
2. It is insensitive to offset waves; hence it can be set to cover more of the protected section without risk of overreaching.



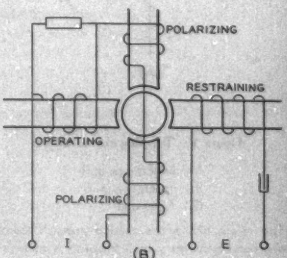


Figure 5

A. Characteristic of reactance unit
B. Schematic connections of reactance unit

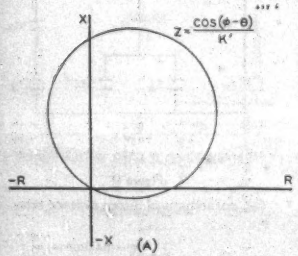
3. Its distance reach is not affected by variation in generation as an overcurrent relay would be.
4. It is relatively insensitive to power swings.

Directional Time Overcurrent Relay

Conventional overcurrent relays will not clear faults during periods of minimum generation if the short-circuit current then is less than the maximum load current with maximum generation, unless the settings of the overcurrent relays are changed between maximum and minimum conditions.

The substitution of a mho unit for the conventional directional unit solves this difficulty by permitting overcurrent settings of less than normal load to be used all the time. In other words, if the directional relay has a voltage restraint, it becomes a mho unit and will not operate nor, with the usual directional control arrangement, permit the overcurrent unit to operate unless the impedance presented to the relay falls sufficiently to indicate a fault on the line.

A widely used type of directional overcurrent relay has an induction cylinder directional unit with alternate potential and current coils around the cylinder. It



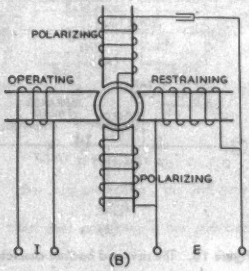


Figure 6

A. Characteristic of mho unit
B. Schematic connections of mho unit

is necessary only to replace some of the current coils with potential coils to provide an E^2 restraining torque, while the remaining coils provide the EI directional torque and thus, change the directional unit into a mho unit.

The directional overcurrent relay with this mho characteristic can be provided with current taps from $1^1/_2$ to 6 amperes on the overcurrent unit instead of the usual 4- to 16-ampere taps. The more sensitive overcurrent settings permit operation on low-current faults, and faster operation can be obtained on heavy faults.

Three-Step Distance Relay

The conventional distance relay consists of a directional unit, a timing unit, and one or more distance measuring units. An instantaneous step and two time-delay steps are usually provided, the three steps being controlled in distance reach either by three distance measuring units (reactance, impedance, or mho) or by one unit whose distance reach is increased in steps by the timing unit.

The first zone unit is used for instantaneous tripping of faults up to 10 per cent from the remote end of the protected section. The second zone unit clears faults in the neighborhood of the next bus in a delayed time, and the third zone provides backup protection for the relays and breaker in the next section beyond.

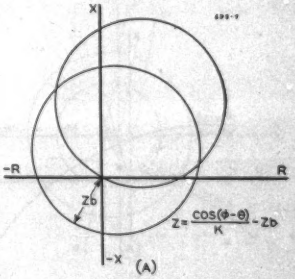
Reactance Distance Relay

A typical 3-step reactance relay, type GCX, has essentially a mho unit for the directional unit so that it provides the third step of measurement. The normal setting of the reactance unit controls the first step. If the fault is beyond the range of the first step, the timing unit changes the setting of the ohm unit after a time delay to increase its reach and provide a second step.

Mho Distance Relay

A typical 3-step mho relay, type GCY, is described in a companion paper.[5] It has three mho units per phase, M_1, M_2, and OM_3, for measuring the three zones and employs a separate timing unit. No directional unit is necessary because each mho unit is inherently directional. This factor provides more effective backup than where all the units depend upon a common directional unit; it also simplifies the circuit and reduces the number of contacts in the trip circuit. Figure 9 shows schematically the d-c tripping connections for one phase. It can be seen that the zone 1 mho unit, M_1, trips directly so that only a single relay contact is required between the battery and trip coil, which is the ultimate in simplicity and reliability.

The third-step mho unit, OM_3, of the GCY relay has a transactor which can offset its impedance characteristic so that it overlaps the origin, as shown in Figure 7. If polarized in the same direction as the first and second steps, M_1 and M_2, the OM_3 unit can be used for out-of-step detection as well as for time-delay backup protection on lines in which the electrical center of the system is located. The out-of-step condition is detected by making the OM_3 impedance characteristic concentric with the M_2 characteristic, as shown in Figure 8, and somewhat larger, so that the changing impedance seen by the relays during a power swing will always operate the OM_3 unit before the M_2 unit. The OM_3 unit then is arranged to pick up an auxiliary relay with a small time delay; blocking is prevented on faults because the M_2 unit de-energizes the auxiliary relay if the OM_3 does not operate first by the margin of the pickup time of the auxiliary relay. The auxiliary relay generally is arranged to pre-



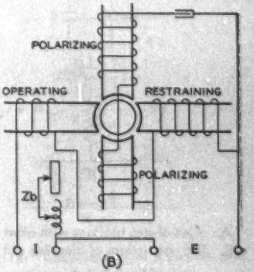


Figure 7

A. Offset mho characteristic
B. Schematic connections of offset mho unit

vent automatic reclosing after a trip on out-of-step conditions but can be used to prevent tripping. It should be remembered, however, that this is necessary only if the relay characteristic circle includes the electrical center of the system, because a mho unit will not trip on out-of-step unless its characteristic is cut by the power swing locus.

In the application of distance relays the first two zones are primarily intended to operate for faults in the protected line section only. Hence they are required to be directional and to operate only for

fault current flowing into the protected line.

The third zone of the distance relay is used for backup protection. As such, it operates only in cases of failure to isolate a fault on some other line section than the one covered by zone 1 and zone 2. Past practice has been to set the third zone element at A of the relays on line AB so that it would operate for a fault at C (see Figure 10A). This meant that the ohmic setting has to equal the line ohms from A to C plus the apparent increase in ohms caused by any fault current fed in at B. Where the line AB is long in terms of secondary ohms, this often resulted in

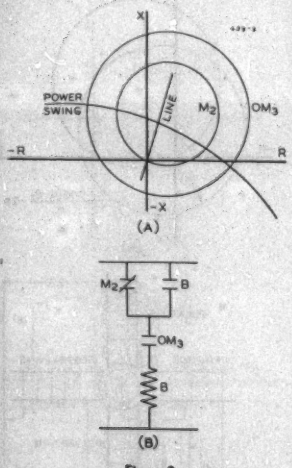


Figure 8

A. Out-of-step blocking with offset mho unit
B. D-c connections of blocking unit

an ohmic setting that would not permit emergency loads to be carried.

With mho relays, since each unit is inherently directional, the third zone tripping direction may be the same as or opposite to that of zone 1 and zone 2. Hence where a third zone setting would be too high in ohms if set in the same direction as zone 1 and zone 2, considerably better settings can be obtained by reversing zone 3. When this is done, the zone 3 element at B on line AB is set to operate for faults at C. The setting in ohms of each zone-3 element is decreased by the impedance of line AB by this reversal, while the over-all protective coverage remains the same. There is no loss of backup protection, since in either case, faults in lines BC or AD result in opening line AB if these faults last for the duration of zone 3 time. In one case, a fault near C opens the breaker at A; in the other case, the breaker at B opens.

It will be seen from Figure 10B that with backup provided by the relay nearest the fault, tap lines in the unfaulted sections will remain in service, whereas with the conventional method of backup, they are lost. On the other hand, it must be understood that failure of the d-c supply or the a-c potential supply could, if it remained undetected, prevent the backup relay from operating, but the conventional backup from the next station would not be affected by this condition. The degree of possibility of such a condition must be weighed against the advantage of improved backup operation when the d-c supply and a-c potential are available.

To summarize, with long lines, adequate backup coverage of the next section often requires such a high ohmic setting for zone 3 in the conventional direction that it may operate on power swings and emergency overload conditions. Hence it is generally advantageous to reverse the zone 3 unit for long lines, especially where some of the sections have tap lines.

Also, where the mho relay is used with carrier, the OM_3 unit must be polarized in the reverse direction from the M_1 and M_2 units because carrier blocking is required only for external faults.

In the case of no tapped lines and no carrier, a check can be made graphically to determine whether the OM_3 unit may operate on power swings and hence whether it is necessary to reverse it. This procedure is described in Appendix II. In such cases a separate offset mho unit is required for out-of-step detection.

Offset Mho Relay

The single-step mho relay can be given an offset characteristic by providing it with a transactor, as described under the heading "Offset Mho Circle." It can be used for out-of-step blocking or backup protection in the same way as has been described for the OM_3 unit of the GCY 3-step distance relay.

When line-to-line faults are not cleared promptly, a power swing may start, and until the fault is cleared, there will be an asymmetrical condition wherein the impedance presented to the relays will be different in each phase. This impedance is a combination of the single-phase impedance of the fault and the balanced 3-phase impedance of the swing. If the relay happens to be connected in the faulted pair of phases, it will measure only the impedance to the fault because the power swing components of current cancel out in the faulted phase pair because of the double current windings of the mho unit. In one of the two remaining phase pairs, the fault current adds to the power swing current and in the other it subtracts from it, so that the impedances measured will be different.

When a power swing follows a fault that has been cleared promptly, it presents a balanced 3-phase condition almost at its inception and certainly before it can operate any out-of-step blocking relays.

For these reasons only one out-of-step blocking relay is required when the system is protected by high-speed relays and breakers, and it can be connected in any phase pair. On the other hand, on systems protected by slow-speed relays and breakers, it is advisable to connect an offset mho unit in each phase so as to ensure recognition of the out-of-step condition and to initiate the blocking as early as possible.

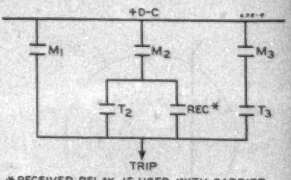


Figure 9

D-c connections of 3-step distance relay

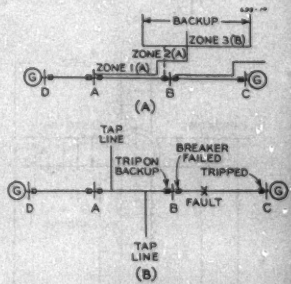


Figure 10. The reversed backup characteristic

A. The time zones
B. Tap lines saved

Applications of the Ohm Unit

Bus Protection

Where a bus section is separated from other circuits by reactors, as shown in Figure 11A, reactance ohm units have

been used to provide protection for the generators and for the bus. Each generator has a reactance ohm unit set to reach into, but not beyond, any of the bus-tie or feeder reactors. A fault in a generator will be cleared immediately because its ohm unit will measure reactance in the reversed direction. A fault on the bus will disconnect all the generators because it will be within the ohm settings of their ohm units.

The main difficulty of conventional differential bus protection is the balancing of the current transformers in all the circuits around the bus to ensure that there is no current to operate the relay during an external fault. This difficulty does not appear with the ohm units because they are connected only to the current transformers in the generator leads.

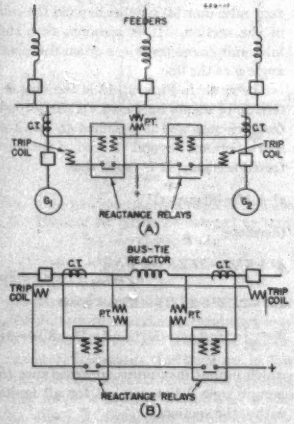


Figure 11

A. Ohm units protecting a bus and generators

B. Ohm units protecting a bus and bus-tie reactor

This form of protection also has been used for bus-tie reactors. Each reactor is protected by two reactance ohm units (Figure 11B) with their contacts in series. The ohm units are polarized away from the reactor so that a fault in the reactor is in the reverse direction for both of them and causes them both to trip and isolate the reactor. A fault on the bus also causes them both to trip and isolate the reactor. In addition, a fault on the bus causes both ohm units to operate, one because it is within its ohmic setting and the other because the fault appears to it in the reverse direction.

Blinders

One application of the ohm unit is to extremely long lines where even the mho unit is not immune to tripping on power swings because the mho circle has to be large in order to cover the long line. In such a case, the straight line characteristic of the ohm unit may be arranged parallel with the line impedance vector so as to cut off one or both sides of the tripping characteristic (Figure 12A) and confine the tripping zone to a strip wide enough to permit tripping on arc resistance.

This scheme was the first attack on the problem of relaying long or heavily loaded lines[3] and is applicable to any form of relay including overcurrent relays. In most applications only one blinder is necessary because the major flow of power generally is in one direction. It is only on interconnections where the maximum power flow is the same in either direction, that two blinders are necessary.

Out-of-Step Tripping

When synchronism is lost, the impedance measured by a relay will pass through the line impedance vector from right to left if the relay is located at the leading or fast end of the system and from left to right if at the lagging end. Two blinders are arranged to operate an auxiliary relay if the impedance crosses the characteristic of one of them before the other, in either direction. This auxiliary relay can be arranged to operate an alarm, trip a breaker, or initiate some form of control.

The advantages of this form of out-of-step relay are:

1. Its operation is not affected by variation in the location of the electrical center of the system.

2. It will not trip under any fault conditions.

3. It trips instantly after the first half cycle of system oscillation. Existing relays require the machine to slip several poles before they will operate.

4. Distinction can be made between speeding up and slowing down of the local generation.

A single-phase relay is adequate for tripping on out-of-step because the regular protective relays will trip during a fault. If the swing continues after the fault has been cleared or if the swing was caused by switching of load or generation without a fault, only a single-phase out-of-step relay is required for tripping because all three phases act similarly.

Reclosing

By means of auxiliary relays, reclosing is prevented after a time-delay trip and after a trip on loss of synchronism. The first is accomplished by an auxiliary relay whose coil is energized whenever the tripping circuit is completed through the timing unit contacts and whose contacts open the reclosing circuit; the connections of this relay are shown in Figure 5 of the companion paper.[5] The second is accomplished by an offset mho unit in a manner already explained earlier in this paper under the heading "Mho Distance Relay."

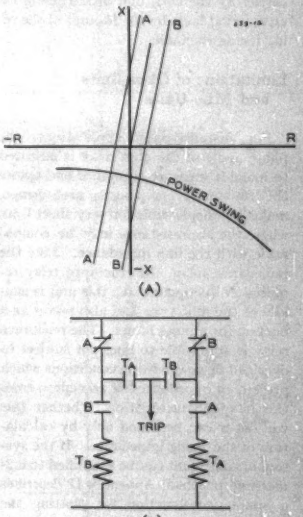


Figure 12. Characteristics of a pair of ohm units for out-of-step tripping

Carrier Relaying

The application of ohm relays to carrier has been discussed in previous papers. The use of mho relays for carrier is the same in function, but the self-contained directional and power swing blocking features of the mho unit simplify the d-c circuits very considerably (Figure 9) and minimize the possibility of sneak circuits.

Mho carrier alone was described in an earlier paper. When carrier is added to mho distance relays, it is necessary only to add two relays containing ground directional and carrier auxiliary elements. The

chief difference between the addition of carrier to mho distance relays and to impedance or reactance relays is the use of the reversed offset mho unit instead of the impedance unit for starting carrier. Figure 13 shows how the OM_3 unit of the 3-step mho distance relay can provide the necessary blocking on external faults with the minimum tendency to operate on power swings and heavy loads.

The OM_3 unit is extremely fast for an induction-type unit. Its minimum time is one-fourth cycle. The time with an average fault is about one-half cycle. This provides a considerable margin of safety between the starting of carrier by the OM_3 unit and tripping for an external fault by the M_2 unit of the relay facing the fault.

Limitations of Ohm Units and Mho Units

For distance-relay applications, the phase angle of the ohm relay is adjusted to make it measure reactance and ignore the resistance component, and, hence, make it indispensable for very short lines where the arc resistance may be comparable with the line impedance. Like the impedance relay, the reactance relay requires a directional unit; this unit is usually of the mho type and also serves as a backup for remote faults. The reactance relay is applicable to lines not subject to overload or power swing conditions which present an impedance low enough to cross the relay characteristic. Whether this will occur can be found only by calculation of the swing impedance. If the system arrangement can be simplified to a 2-machine problem, Appendix II describes a simple construction for plotting the swing impedance.

The phase angle of the mho relay can be adjusted to be approximately the same as that of the line. This ensures the smallest reach at right angles to the line impedance vector, and hence the least tendency to operate on power swings that may be expected on long lines and on heavily loaded lines of medium length. The potential polarizing winding of the mho relay limits its application to long lines because, even with memory action, the torque is likely to be low on very short lines during second zone fault, after the memory action has expired.

Arc resistance also places a limit on the shortness of a line to which the mho unit can be applied. Arc resistance increases as the current decreases and becomes more effective on shorter lines. This is in the same direction as the other limitation of minimum voltage to provide adequate

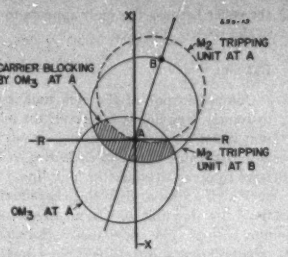


Figure 13. Carrier blocking with offset mho unit

torque. Since the arc resistance limitation is more severe, we shall consider it in detail.

Minimum Length of Line

From the ohmic characteristics in the companion paper[3] on the "Mho Distance Relay," it will be seen that the accuracy of the GCY relay is within ten per cent variation down to eight volts at the relay terminals. This means that if the instantaneous zone is set to cover 90 per cent of the protected section, it may cover only 81 per cent of the section if the section is so short or the fault current is so small that the IZ drop is only eight volts secondary. Although in many cases a greater variation may be permissible, this value will be taken for the purpose of establishing a limit. It should be realized, however that this value has no relation to the ability of the relay to operate reliably on faults within the protected zone because the actual pickup of the relay is around $1^1/_2$ volts.

Hence for accurate operation, IZ equals eight volts at the relay terminals for a fault at the ohmic setting of the M_1 unit. From this fact, we can determine the minimum line length and fault current for which the relay can be set. Changing to primary phase to neutral values, we have $IZ = 8R_p/\sqrt{3}$, where I is the minimum fault current, Z the ohmic setting of M_1, and R_p is the ratio of the potential transformers. If M_1 is set to cover 90 per cent of the protected section, which is L miles long and has an impedance of 0.9 ohm per mile, then

$$I \times 0.9 \times 0.9L = \frac{8{,}000 \text{ kv}}{115\sqrt{3}}$$

or

$$L = \frac{50 \text{ kv}}{I} \text{ miles}$$

In other words, the relay is applicable to lines down to a minimum length of 50 kv/I miles, where I is the minimum fault current, and kv is line-to-line voltage in kilovolts.

Arc Resistance

The presence of arc resistance will reduce the reach of the mho relay. A small reduction of the instantaneous zone is acceptable, but the intermediate zone always must reach beyond the next bus, that is, faults within the section must not trip in zone 3 time, or selectivity between stations will not be possible.

In Figure 14A, R is the arc resistance, Z is the impedance of the protected section, ϕ is its phase angle ($\tan^{-1} X/R$), and K is the fraction of Z by which the second zone mho unit M_2 reaches beyond the end of the section. It is assumed that the mho unit characteristic is given the same angle ϕ as the line.

The circle in Figure 14A is the characteristic of a mho unit used for the second distance step and is assumed to reach a short distance beyond the end of the protected section. It is noted that

$$a^2 + b^2 = (\text{diameter})^2$$

therefore,

$$R^2 + K^2Z^2 - 2KZR\cos\phi + R^2 + Z^2 + 2ZR\cos\phi = (Z + KZ)^2$$

$$2R^2 - 2KZ^2 + 2RZ(1-K)\cos\phi = 0$$

$$R = \frac{Z}{2}\left[\sqrt{\cos^2\phi(1-K)^2 + 4K} - (1-K)\cos\phi\right]$$

which equals maximum arc resistance to permit zone 2 time or less for all faults within the section.

If M_2 is set for 20 per cent beyond the next bus, $K = 0.2$. Assuming $\phi = 60$ degrees, then, from the formula, $R = 0.29Z$ or $Z = 3.45R$.

The initial arc resistance, assuming 16 kv per foot of insulator string and 440 volts per foot of arc,[4] is

$$R_{arc} = \frac{440}{I_{pri}} \times \frac{\text{kv}}{16\sqrt{3}} \times \frac{115\ C.T.}{1{,}000 \text{ kv}}$$

$$= \frac{1.83}{I_{sec}} \text{ ohms phase-to-neutral}$$

With a fault drawing five amperes secondary, $R_{arc} = 1.83/5 = 0.36$ ohm phase-to-neutral. Since $Z = 3.45R$, from a preceding formula, $Z = 1.24$ ohms for the minimum secondary impedance of a line section that can be protected safely with mho relays.

Where the line impedance is less than 1.24 ohms secondary, each case should be examined individually. If there is a heavy short-circuit current, the arc voltage will be less than 440 volts per foot.

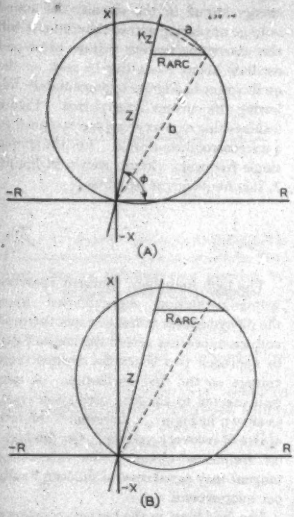


Figure 14

A. Arc resistance shortens reach of mho unit
B. Effect of arc resistance reduced by leading mho characteristic

On the other hand, if the fault occurs near the station, the number of insulators may be higher and the arc resistance proportionately increased; furthermore, at low short-circuit currents, the volts per foot may increase to 600 or 1,000 and should be checked from the formula $R_{arc} = 8{,}750L/I^{1.4}$ ohms, where L is the arc length in feet.

If the arc resistance is too high for a reasonable application, some leeway can be obtained on highly lagging lines by setting the mho relay characteristic at a less lagging phase angle than that of the line impedance. This permits more arc resistance anywhere in the section before the relay will fail to pick up (see Figure 14B) or permits the normal application down to one ohm impedance.

Conclusions

The product-type impedance unit is a very useful relay tool whose flexibility enables it to cover the entire field of transmission line protection with simpler circuits and better characteristics than heretofore.

The only limitations to the application of current and potential polarized units are those which prevent either from covering the whole range alone. The natural field for current polarized distance relays is short lines and ground fault protection; interphase faults on long or heavily loaded lines require potential polarized (mho) distance relays.

Appendix I

The characteristic of any ohmic relay on an impedance diagram is a circle. This is because the torque from any form of electromagnetic drive is proportional to the square of the flux or to the product of two fluxes, and the fluxes in turn are proportional to the currents or potentials. The torque[1] of a relay having current and potential windings must therefore be of the form

$$KI^2 - K'E^2 + EI\cos(\phi - \theta)$$

where K and K' are winding constants, ϕ is the phase angle of the protected circuit, and θ is the angle of the relay characteristic. At the balance point of the relay, the torque is zero and the equation for balance is

$$KI^2 - K'E^2 + EI\cos(\phi - \theta) = 0$$

This general equation of a relay has the two main variables E and I, which can be reduced to one by changing it to an impedance diagram.

Dividing the equation through by $K'I^2$, we get

$$\frac{K}{K'} - Z^2 + \frac{Z\cos(\phi - \theta)}{K'} = 0$$

Transferring K/K' to the right-hand side and adding $(1/2K')^2$ to both sides, this equation becomes

$$Z^2 - \frac{Z\cos(\phi - \theta)}{K'} + \left(\frac{1}{2K'}\right)^2 = \frac{1 + 4KK'}{(2K')^2}$$

This is the equation of a circle of radius $\sqrt{1+4KK'}/2K$, whose center is $1/2K'$ from the origin at an angle θ from the reference vector R (see Figure 15).

The constants K and K' are functions of the turns, and so forth, of the current and potential windings respectively. These constants can be determined from the impedance circle by solving for K and K' in the expressions for the radius and the location of the center. For instance, a 4-ohm circle at 60 degrees with one ohm offset in the direction of the origin has a radius of two and its center is one from the origin. $1/2K' = 1$, or $K' = 1/2$, and substituting this value in the expression for the radius, $\sqrt{1+4KK'}/2K'$, we get $\sqrt{1+2K} = 2$, or $K = 3/2$. Hence the equation is

$$\frac{3}{2}I^2 - E^2 + EI\cos(\phi - 60^\circ) = 0.$$

This equation is typical of the offset mho characteristic in Figure 7A.

Appendix II. Power Swing Check

A simple geometrical construction can be used to determine whether a relay will operate during a swing condition. This method assumes that the system can be simplified to an equivalent system of two machines separated by impedance. It determines the angle between the machines at which the relay will operate. Thus, it can be used to determine whether a reactance or impedance relay should be replaced by a mho relay, whether to reverse the third zone or not, or whether a blinder is needed to prevent the M_1 and M_2 units from tripping on a very severe power swing.

Referring to Figure 16, AB is the impedance of the protected section, SA is the

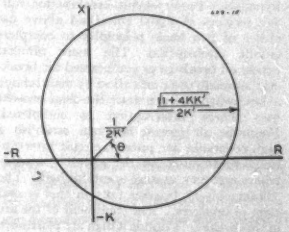


Figure 15. Impedance characteristic corresponding to general relay equation $KI^2 - K'E^2 + EI\cos(\phi - \theta) = 0$

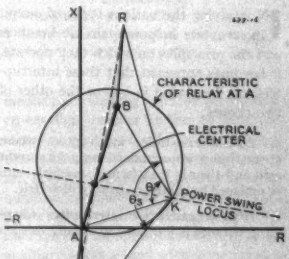


Figure 16. Construction for checking operating point of relay on a power swing

system impedance beyond terminal A, and BR is the system impedance beyond terminal B.

Draw a perpendicular through the midpoint of RS. From the point K where it cuts the relay characteristic, draw lines to R, S, A, and B. RKS is the angle θ_s between the generated electromotive forces at R and S at which the relay at RA will trip. BKA is the angle θ between the terminal voltages at A and B at which the relay at A will trip, and AK is the impedance it sees.

The power swing locus is shown as a straight line. This implies equal generated

The Development, Design, and Performance of Magnetic-Type Power Circuit Breakers

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Synopsis: Power circuit breakers for voltage services of 2,300 volts and above use either of two basic principles to complete circuit interruption. The more familiar types, oil breakers or compressed air breakers, complete their operation by maintaining a low resistance arc until the final current zero where interruption is completed. Magnetic air circuit breakers establish a high resistance arc prior to circuit interruptions which modifies the circuit constants before recovery voltage is established. The "Magne-blast" breaker falls in this second class of breakers. The treatment of the arc in this breaker to obtain a high arc resistance is explained in some detail. Also, design practices and operating characteristics of the final magnetic type breaker are reviewed.

IN studying the various types of circuit interrupters in power circuit breakers and the principles on which they operate, it becomes apparent that these interrupters can be placed in one or the other of two classes:

1. Low-arc-resistance interrupters whose arc resistance is maintained low until current zero and then is transformed suddenly into or replaced by a high-resistance dielectric.

2. High-arc-resistance interrupters whose arc resistance is increased gradually to such a high value prior to current zero that arc re-establishment is made impossible following current zero.

Low-Arc-Resistance Interrupters

Power circuit breakers rated 2,300 volts and above generally have functioned as low-arc-resistance interrupters. They are recognized as oil blast breakers, impulse breakers, air blast breakers, and so forth. These breakers interrupt the circuit by drawing a short low-resistance arc in some type of control chamber where a blast of insulating fluid is directed at it. To complete the interruption at current zero, the low resistance of the arc gap must be replaced abruptly by a high-resistance dielectric. This type of interruption can be understood best by reference to the typical oscillograms of a short-circuit interruption shown in Figure 1. In this oscillogram the breaker contacts part at t_0 and the short-circuit current I is interrupted at t_1. During the arcing period ($t_0 - t_1$), the arc resistance remains so small that the arc-resistance voltage drop e_a at no time rises to more than a few per cent of the generated voltage (shown dotted). The introduction of this low-arc-resistance voltage drop into the circuit does not affect appreciably either the magnitude or the phase angle of the short-circuit current.*

For the circuit to be interrupted as the current passes through zero at t_1, the fluid blast suddenly must increase the low resistance across the contact gap by cooling or displacing the hot ionized arc products to prevent arc re-ignition as the system recovery voltage rises following current zero.

Immediately following current zero at t_1, the voltage across the contacts begins to rise to the system-generated voltage, which at this instant is at its crest (zero power-factor fault). Because of the energy stored in the circuit, the actual voltage appearing across the contacts will rise above the system voltage crest and oscillate about it, as can be seen on the oscillogram in Figure 1, immediately following the current interruption. Figure 2 shows this recovery voltage extended to a microsecond time scale. For the simple single frequency circuit, shown in Figure 3, this frequency is equal to

$$f = \frac{1}{2\pi\sqrt{LC}}$$

The high frequency transient recovery voltage-oscillation superimposed upon the 60-cycle crest voltage causes the total voltage appearing across the contact gap to approach two times the normal crest voltage on the first oscillation. A tangent erected to the first oscillation crest, as shown in Figure 2, determines the rate of rise of recovery voltage. On the highest frequency circuits, this rate-of-rise tangent may equal several thousand volts per microsecond.

The fluid blast in the low-arc-resistance type of interrupter must increase the insulation strength between its contacts immediately following current zero fast enough to withstand this rate of rise of recovery voltage to prevent arc re-establishment after current zero. As the actual rate of rise of recovery voltage encountered in practical applications varies between wide limits, various configurations of low-arc-resistance interrupters have been designed to insure the required fluid velocity to interrupt the highest recovery-rate circuits.

In many breakers using low-arc-resistance interrupters in which the high-velocity fluid blast bodily displaces the low resistance-arc gases, the resistance of the arc gap rises abruptly at current zero to substantially infinity immediately following current zero. These breakers are capable of withstanding rates of rise of recovery voltage higher than any which can be encountered in service and can be duplicated only in the laboratory.

In other breakers using low-arc-resistance interrupters, an auxiliary resistor is inserted into the circuit following the current zero to limit the rate of rise of recovery voltage. Such resistors, shunted into the circuit in parallel with some portion of the contact break, absorb the energy of the transient voltage-oscillations. Applications as now practiced are

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electromotive forces and no line capacitance. These assumptions simplify the construction and have negligible effect on the angles θ and θ_2 at which the relay operates.

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*The actual instantaneous values of arc resistance r_a are proportional to the arc length and are an inverse function of arc current because the arc diameter increases and decreases with current. As the short-circuit current approaches zero, r_a will increase proportionately, but the voltage drop in the arc e_a, which equals $i_a r_a$, will remain low.

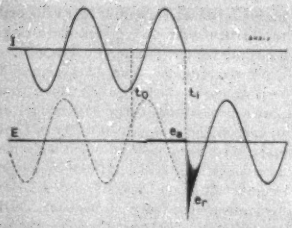


Figure 1. Typical short-circuit interruption by low-arc-resistance type of interrupter (fluid blast) showing high-frequency transient immediately following interruption

E = generator voltage
I = short-circuit current
e_a = arc voltage drop (small on account of low arc resistance)
e_r = transient recovery voltage appearing across contacts of breaker immediately following interruption
t_0 = instant of contact parting
t_1 = instant of circuit interruption

successful in holding the rate of rise of recovery voltage to moderate values, definitely limit the severity of circuit transients, and reduce the rate at which gap resistance must be built up across the contacts.

Such resistors also have proved of value when interrupting faulted circuits to stabilize the clearing of transmission lines, discharging the capacitance charge remaining on the line faster than the generated voltage reverses and thereby preventing possible restriking at the breaker contacts because of excessive overvoltage stresses.[13]

High-Arc-Resistance Interrupters

The high-arc-resistance interrupter, as contrasted with the low-arc-resistance interrupter, builds up a high arc resistance prior to current zero, thereby modifying the circuit current and achieving an early interruption by advancing the current zero to, or near, the recovery voltage zero. The rate of rise of recovery voltage also is held to very low values, a factor which permits the build-up of insulation across the electrodes at the moderate rates achieved by rapid cooling of the arc column. The more successful interrupters of this type are recognized as magnetic-type circuit breakers.

With any magnetic-type air circuit breaker, the arc magnetically is forced to loop away from the contacts and may travel out on diverging arc runners where its length is further increased many times. As the arc is lengthened and cooled, its resistance increases rapidly so that the resultant resistance voltage drop in the arc column becomes an appreciable percentage of the total circuit voltage. This high-resistance-arc drop has a two-fold effect on the short-circuit current:

1. It reduces the magnitude of the short-circuit current to a fraction of its previous value.

2. It improves the power factor of the circuit bringing the current more nearly into phase with generated voltage, causing the current zero to occur near a voltage zero rather than its normal 90-degree lagging or crest position.

These effects can be seen best by reference to the typical interruption with a magne-blast breaker shown in Figure 4. Here the voltage drop in the arc column rises at a rate of several thousand volts per half-cycle so that the short-circuit current in the last half-cycle is reduced to approximately half its original value. Moreover, the introduction of the arc resistance into the circuit has advanced the current zero from the normal crest point on the generated voltage wave, in this case to approximately one-half crest voltage.

As the instantaneous system voltage at the point of current zero has been reduced greatly, the amplitude of the high-frequency oscillation is reduced correspondingly. This reduction in amplitude of the high-frequency oscillation will reduce the circuit rate of rise of recovery voltage in direct proportion even if the resistance of the arc column were raised to infinity immediately following current zero.

In this type of breaker, however, it has been found that the long hot gaseous post-arc stream between the arc runners immediately following current zero affords an excellent resistor further to damp out recovery voltage-oscillations. Although the resistance of this cooling column of arc gases r_a increases to infinity in a few hundred microseconds after current zero, it is a recovery-rate-limiting resistor just after current zero, fully as effective as the auxiliary resistor used with some types of low-arc-resistance interrupters. The manner in which the pre-current zero arc resistance varies during the current-zero period as plotted from a typical interruption is shown in Figure 5A.

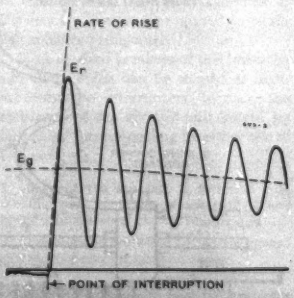
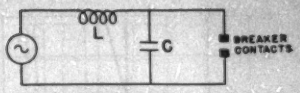


Figure 2. Transient recovery voltage across contacts of low resistance breaker following interruption.

The dotted line tangent to the first oscillation is the rate of rise of recovery voltage



L = INDUCTANCE OF CIRCUIT
C = INHERENT CAPACITANCE OF CIRCUIT

Figure 3. Simple single-frequency test-circuit

$$\text{Oscillating frequency} = f = \frac{1}{2\pi\sqrt{LC}}$$

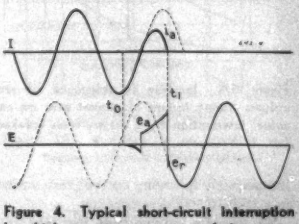


Figure 4. Typical short-circuit interruption by high-arc-resistance type of interrupter (magne-blast) showing high-arc-resistance voltage drop during arcing period which results in marked reduction in both short-circuit current and transient recovery voltage

E = generator voltage
I = short-circuit current
e_a = arc voltage drop (high on account of high arc resistance)
e_r = transient recovery voltage
t_0 = instant of contact parting
t_1 = instant of circuit interruption

The resistance r_a, of this cooling gaseous column immediately following current zero will vary with

1. The design of the arc chute, which determines the rate of cooling of the hot gases.

2. The magnitude of the current being interrupted, which determines the cross section of the hot gas column.

The initial resistance of this hot gaseous column varies inversely with the short-circuit current being interrupted. This means that the maximum rate of rise of recovery voltage which can appear across the breaker terminals will decrease as the value of short-circuit current is increased. Figure 5B shows how this resistance r_a

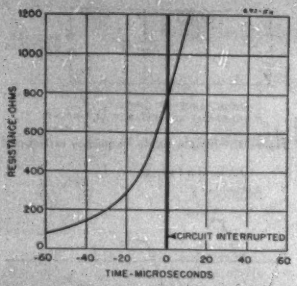


Figure 5A. Increase in resistance of arc column during instant of current zero on an actual interruption by a magne-blast breaker

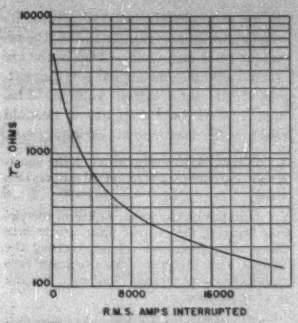


Figure 5B. Variation of arc column resistance r_a following interrupting current zero versus short-circuit current being interrupted

immediately following current zero varies in a 5-kv 100,000-kva breaker.

On circuits having very low inherent capacitance C and high natural rates of rise of recovery voltage, the resistance of this cooling arc column r_a will damp out entirely the oscillating frequency. To do this, the ohmic value of r_a must be less than the critical damping resistance of the circuit, or $r_a < 2\sqrt{L/C}$.

The total effect of the high-resistance-arc type of breaker on the rate of rise of recovery voltage appearing across its terminals may be seen by reference to Figure 6. Here is shown the rise of recovery voltage following an interruption with a magne-blast breaker extended to microsecond scale. For comparison, the dotted curve shows the recovery oscillation which occurs with a low arc resistance interrupting the same circuit at a crest voltage point and without benefit of arc resistance following current zero. Besides the radical reduction in the rate of rise of recovery voltage shown with the magnetic breaker, the first peak of transient recovery voltage-oscillation is reduced from 1.9 times normal crest to 0.35 times normal crest.

The magne-blast breaker has proved that the operation of magnetic air breakers, when properly designed, is independent entirely of natural oscillating frequency or inherent rate of rise of circuit recovery voltage.

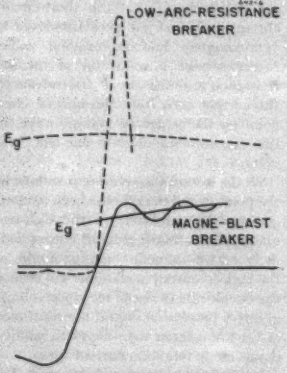


Figure 6. Transient recovery voltage obtained with high-arc-resistance breaker (magne-blast breaker) shown full as compared with transient recovery voltage of low-arc-resistance breaker (fluid blast) shown dotted

Development of High-Arc-Resistance Interrupter Designs

There have been many interesting attempts to develop pure resistance interrupters that might function with little or no arcing. Several years ago the authors made and tested a resistance interrupter designed to interrupt high values of alternating or direct current at 600 volts and to do this with no appreciable arcing. This interrupter (Figure 7) consisted of a stack of graduated wafer-like compound resistances whose composition varied from pure copper, through copper carbon mixes to carbon clays, to a final wafer of fired clay. It was to function much the same as a large rheostat being turned into the circuit. Although the tests on this device demonstrated the need for much improved commutation before arcing could be eliminated at high currents, they did confirm the value of resistance as an interrupter. In a later investigation the arc itself was used as a suitable commutating "brush" to insert a series of ceramic resistance rods into the circuit. These resistance rods were U-shaped and were so arranged that a series of arcs would travel up between them to insert their resistances into the circuit being interrupted, as shown in Figure 8. The separate series arcs were moved up these electrodes by concentrated magnetic fields. This arrangement was acceptable in its performance up to 100,000 kva at 5,000 volts. A careful analysis of its operating characteristics, however, showed that the series arcs were contributing the major portion of the resistance required for successful interruptions and that the complex ceramic resistance rods hardly were justified. This was true particularly if the arcs were controlled properly. Successful air breakers have been built using resistance arc runners, but even in these designs the arc contributed much more resistance than did the runners.

These early studies firmly established the value of a controlled and confined arc

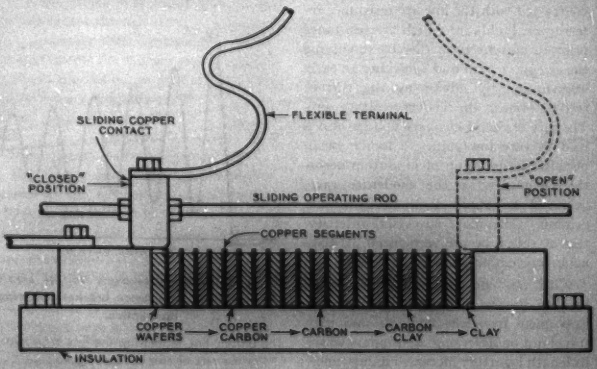


Figure 7. Graduated resistor breaker made up of gradually increasing resistance elements

Figure 8. Disassembled arc chute of high voltage breaker using U-shaped resistor rods inserted in circuit by short arcs

The photograph was taken after high-current tests

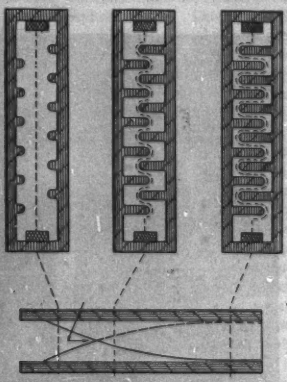


Figure 9. Interleaving fin type of arc chute obtaining arc lengthening in more than one plane by serpentine configuration

in air as a controllable resistor for the interrupters of power circuit breakers. A study then was initiated to determine the most effective way of controlling and confining the arc to establish the proper high-resistance characteristics.

There is a history of successful low-voltage air breakers (600 volts and below) that operate as high-arc-resistance interrupters. The most common arrangement is recognized as the plain break low-voltage circuit breakers where the arc is established between separating electrodes and is cooled and extinguished in open air. Although such circuit breakers are satisfactory interrupters, given sufficient space and time, they are limited in their physical applications because of the long arc in open air required to establish sufficient resistance.

More modern breakers of this low-voltage class, which can be classed as high-arc-resistance interrupters, increase the resistance of the arc per unit length by increasing the arc-cooling by either one of two methods:

1. Forcing the arc into a series of cold metallic pins or plates which cool it and break it into several shorter arcs.

2. Forcing the arc between closely spaced sidewalls of cool ceramic insulation.

When attempting to cool the arcs of a breaker for higher service voltages (2,300 to 15,000 volts) to extinction, it soon became apparent that the necessary arc length in a metallic pin or plate-type arc chute requires greater physical dimensions

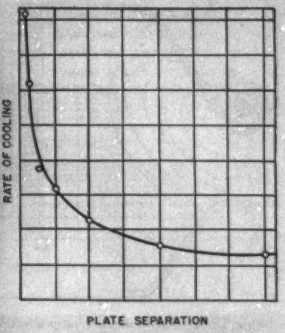


Figure 10. Variation in arc cooling with spacing between insulating plates

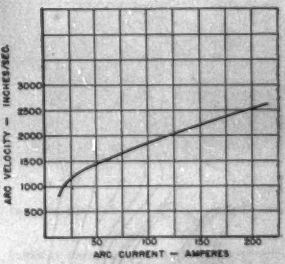


Figure 11A. Variation in arc velocity with arc current in constant transverse magnetic field of 400 gausses

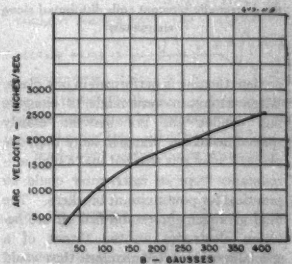


Figure 11B. Variation of arc velocity with transverse magnetic-field strength of 200-ampere arc between parallel arc runners

than the compact design of switchgear equipment for these voltages now affords. Neither can insulating-plate types of arc chutes for these voltages be accommodated to obtain sufficiently high arc resistance in the allowable spacing of modern metal-enclosed equipment if all

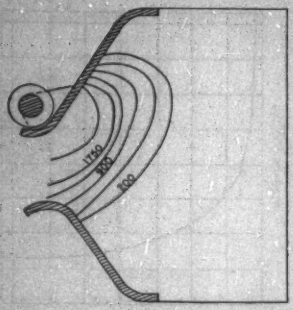


Figure 12A. Poor transverse magnetic-field distribution over area of arc chute resulting from use of single strong magnetic blowout coil

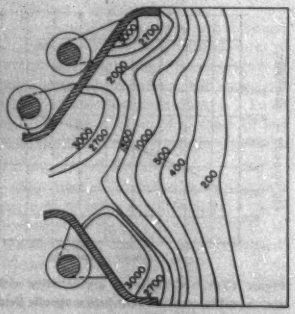


Figure 12B. Improved transverse magnetic-field distribution over area of arc chute with three magnetic blowout coils distributed along arc runners

arc lengthening is performed in one plane. When attempts were made to elongate and confine the arc between closely spaced insulating plates in more than one plane, it soon was realized that a high-arc-resistance type of interrupter could be practical for power circuit breakers. The final arrangement established an arc between electrodes at the throat of a specially constructed arc chute that would force the arc up between interleaving fins of ceramic insulation. This arc movement forced it into a closely confined serpentine pattern of considerable length.

In 1939 the first magne-blast breaker for voltages up to 5,000 volts was presented before the Institute.[3] It used a specially designed arc chute with tapered insulating fins alternately spaced from the inner sidewalls to form an interleaving path for the arc column. As the arc column is forced magnetically into this chute, it is folded back and forth between these fins to extend its length to many times the longitudinal distance between the arc runners, as is shown in Figure 9.

By this construction, an arc chute with a one-foot spacing between arc runner tips creates an arc path several feet in length, depending on the length and amount of overlapping of the interleaving ceramic fins in the chute between the runners. Besides greatly increasing the length of the arc, these closely spaced fins come into very intimate contact with the arc column, flattening it out of its naturally circular cross section. The intimate contact thus effected between the high-temperature arc column and the cool surfaces of the fins extracts heat from the boundary layers of the arc column at a rapid rate, giving a high arc-resistance per unit length. Suits has shown the rate of cooling in an arc column to increase as fins are brought closer together in accordance with the curve shown in Figure 10.

The cooling rate of the arc by the closely spaced fins determines the voltage drop per unit length e_1 in the arc column. The total voltage drop in the arc column e_a is equal to

$$e_a = e_1 l$$

where

e_a = total resistance voltage drop in arc column
e_1 = resistance voltage drop per unit length
l = total length of arc

The total arc-resistance voltage drop e_a required for circuit interruption of a given current is directly proportional to the system voltage E_m. This may be demonstrated easily by connecting two arc chutes in series and noting the double voltage which may be interrupted. If the fin spacing which determines e_1 is held constant, it is then necessary to increase the total arc length l in direct proportion to the circuit voltage. As the number of fins determines the total interleaving arc length, the number of fins required in the arc chute in the magne-blast breaker is proportional to the rated voltage of the breaker

Magne-Blast Design

The Interrupter

The material from which these fins are made is a highly heat-resistant dielectric developed specially for magnetic-breaker arc chutes. As the temperature of the arc column is several thousand degrees centigrade, it loses its heat to the fins by forming a thin molten glaze on the fin surfaces. Immediately following the passage of the arc, this glaze solidifies and its heat passes into the body of the chute. The relatively great mass of the chute provides sufficient thermal storage to accept repeated operations far beyond any service requirement. Because this phenomenon is one entirely of thermal conductance, there is no physical change in the arc chute. As the same thickness of glaze becomes molten and solidifies on each operation, no deterioration in the materials of the arc chute is apparent during the life of a circuit breaker.

Figure 13. Test setup of magne-blast breaker with small quartz rods projecting into side of arc chute to serve as windows for taking high-speed photographs

Figure 14. Actual photographs taken with Rankin high-speed camera showing arc behind windows

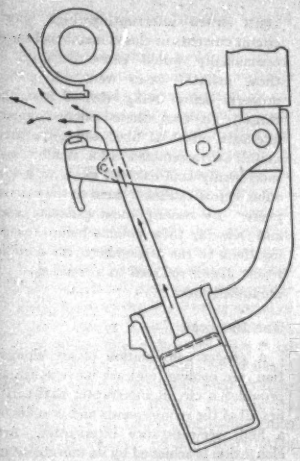
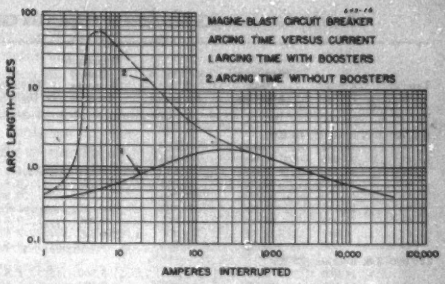


Figure 15. Cross section of piston air booster and movable contact

Figure 16. Curve of arcing time versus current of arc chute with piston booster (solid curve) as compared to arcing time without piston booster (dotted curve), showing drastic reduction in arcing time at lower values of short circuit in magnetic air breaker



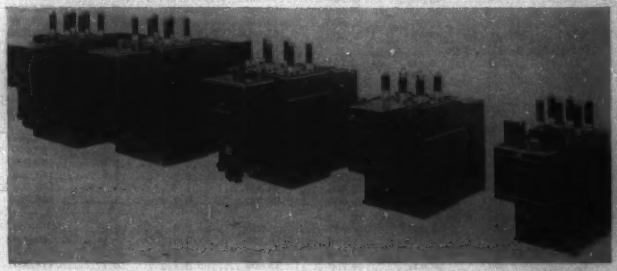


Figure 17. Complete line of magne-blast breakers rated 50,000 to 500,000 kva for use in vertical lift metal-clad switchgear

The faster the arc is moved over these fins of the arc chute, the cooler the fin surfaces will remain and the greater is its cooling effect on the arc. This arc speed is a function of both the current flowing in the arc column and the strength of the transverse magnetic field. Figure 11A shows the variation in velocity of an arc in free air when only the current is varied, while Figure 11B shows the velocity variations of an arc in free air when the transverse magnetic field is the only variable.

It is apparent that a strong uniform magnetic field must be established over the entire working area of the arc chute for maximum arc-chute efficiency. To obtain maximum field-strength uniformity in the larger arc chutes for the higher voltage breakers, it is necessary to use several blowout coils distributed along the arc runners. Several small blowout coils have proved much more effective than a single powerful coil because the magnetic field strength decreases rapidly with the distance away from the coil as a result of leakage flux. This can be seen by reference to Figure 12A which shows the poor field-strength distribution which is obtained over an 18-inch arc chute with a single strong blowout coil. The low flux density reduces materially the arc speed at the extremities of the chute. This would cause arc slowing or arc lingering near the chute extremities, resulting in high local heating and poor arc cooling. The addition of two more blowout coils, as shown in Figure 12B, improves this distribution considerably and maintains a high arc speed over the entire working area of the arc chute.

To study better the effects of localized magnetic blowout coils on arc speed, a special high-speed motion-picture camera developed by Mr. Rankin was used to photograph the movement of the arc through the chute. The extreme speed of this camera (120,000 frames per second maximum) is capable of recording the position of the arc as it passes by tiny quartz windows scattered across the chute sidewalls. Figure 13 pictures the set-up of a magne-blast circuit breaker used for this investigation. The windows are 5/16-inch-diameter quartz rods which project through the magnetic side plates, insulation, and arc-chute side and are flush with the inner ceramic surface. Actual photographs showing this recorded arc travel are shown in Figure 14.

The faster the arc moves into the arc chute, the more rapidly its resistance will increase, resulting in a more rapidly increasing arc-resistance voltage drop e_a. The more rapidly e_a rises, the greater will be the reduction of short-circuit current i_a and the shorter the arc duration $t_b - t_1$. For very high rates of increase in arc

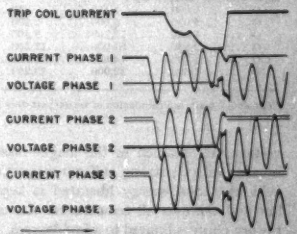


Figure 18A. Oscillogram of 3-phase short-circuit interruption at 560,000 kva, 13,000 volts, showing large reduction in last loop of short-circuit current prior to interruption

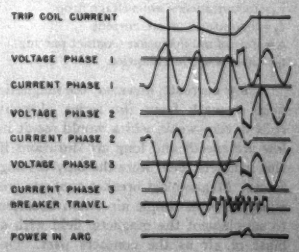


Figure 18B. Oscillogram of 3-phase short-circuit interruption at 550,000 kva, 14,500 volts

Table I. Performance Characteristics of Magne-Blast Circuit Breakers*

Type of Test	Circuit Voltage	Maximum Peak Amperes	Maximum Rms Amperes	Maximum Rms Amperes in Arc	Cycle Arc Duration	Cycles Trip to Interruption	3-Phase Kilovolt-Amperes
500,000-Kva Breaker, 15 Kv							
O	14,500	2,800	1,650	1,580	1.8	4.5	40,000
O	14,500	4,900	2,900	2,900	1.2	3.9	73,000
O	14,500	13,000	8,100	7,500	1.1	3.8	190,000
O	14,500	23,000	13,300	10,200	0.8	3.4	260,000
O	14,500	30,000	18,200	15,800	0.8	3.4	400 000
O	14,500	55,000	33,000	22,000	1.0	3.5	550 000
O	13,000	66,000	40,000	22,000	0.8	3.2	500,000
O	6,500	111,000	70,000	46,000	0.6	2.8	520 000
CO	6,500	110,000	70,000	44,000	0.6	2.8	500,000
250,000-Kva Breaker, 15 Kv							
O	14,500	5,500	3,200	3,000	1.8	4.2	75,000
O	14,500	14,500	7,000	7,000	1.1	3.8	175,000
O	14,500	22,000	13,000	11,000	0.9	3.3	280,000
O	11,000	42,000	26,000	16,300	0.8	3.2	310,000
O	6,600	46,000	27,000	22,000	0.8	3.2	260,000
CO	11,000	40,000	22,000	13,100	0.8	3.2	250,000
CO	6,600	48,000	27,000	23,000	0.8	3.2	260,000
250,000-Kva Breaker, 5 Kv							
O	5,000	5,400	3,200	2,300	1.6	3.6	30,000
O	5,000	24,000	14,400	11,600	1.0	3.0	100,000
O	5,000	47,000	28,000	23,000	0.9	2.9	200,000
O	5,000	65,000	38,000	34,000	0.8	2.6	290,000
CO	4,200	84,000	50,000	34,000	0.7	3.7	250,000
150,000-Kva Breaker, 5 Kv							
O	5,000	1,200	720	610	2.4	4.5	5,300
O	5,000	13,500	7,800	6,600	1.1	3.1	57,000
O	5,000	29,000	17,000	14,400	0.8	2.8	130,000
O	5,000	46,000	27,000	21,000	0.9	2.9	180,000
CO	5,000	63,000	37,000	20,000	1.0	3.0	170,000
CO	2,300	80,000	49,000	38,000	0.7	2.7	150,000
100,000-Kva Breaker, 5 Kv							
O	5,000	1,560	940	940	2.4	4.4	8,100
O	5,000	13,300	7,700	6,700	0.8	2.8	49,000
O	5,000	29,000	17,000	14,400	0.8	2.8	130,000
CO	5,000	28,000	16,700	15,600	0.7	2.7	110,000
CO	2,300	55,000	33,000	25,000	0.7	2.7	100,000
50,000-Kva Breaker, 5 Kv							
O	5,000	1,350	810	690	3.0	4.4	6,000
O	5,000	5,000	2,900	2,300	1.0	3.4	20,000
O	5,000	15,700	9,400	6,300	1.2	3.6	55,000
O	2,300	32,000	17,500	13,200	0.8	3.2	53,000
CO	4,200	14,600	8,800	7,200	1.0	3.4	54,000
CO	2,300	32,000	19,200	13,800	1.1	3.1	55,000

*The above table is a tabulation of actual test data on various ratings of magne-blast breakers.

voltage, as obtained in the magne-blast breaker with its strong uniform magnetic field, the total energy liberated is kept low and the over-all temperature rise of the arc chute is limited to a few degrees.

The total energy liberated in the arc chute during an interruption is equal to

$$\text{Total energy} = \int_{t_c}^{t_i} e_a i_a dt$$

where

e_a = instantaneous arc-voltage drop
i_a = instantaneous arc current
t_c = time of arc initiation (contact parting)
t_i = time of arc interruption

At low currents, however, the magnetic field strength from the series blowout coils is very weak, which would result in low arc speeds and long arc durations if this magnetic field were the only driving force. Magne-blast breaker contacts are equipped with simple air-piston boosters to supplement the magnetic field with a blast of air as the contacts part. On light currents the arc, therefore, is carried into the interleaving arc chute with approximately the same speed as on heavy currents. Figure 15 shows the construction of the contact-assembly piston booster on a 15-kv breaker.

The total arcing time of a typical magne-blast breaker with air booster for all values of current is shown in Figure 16. Tests have shown this arcing time to be entirely independent of the direction in which the arc chute is pointing, whether this direction is upward, downward, or in a horizontal plane. The air-piston booster therefore encourages extreme flexibility in breaker design by permitting the arc chute to exhaust either horizontally, downward, or upward, thereby simplifying the design of this breaker for modern vertical-lift metal-clad equipment. Without the air booster, the arcing time at very light currents would be considerably longer, as shown by the dotted line at the top of the figure. The shape of this dotted curve is generally characteristic of all magnetic air breakers without boosters, regardless of the direction of arc-chute exhaust.

Early studies showed that the incandescent gases exhausted from the chute when interrupting high short-circuit currents in closed metal enclosures occasionally would cause flashover if these exhaust gases were not cooled properly before being released from the chute. To cool these exhaust gases, alternate plates of fiber and corrugated metal are assembled as a muffler and successfully cool exhaust gases to a low value before releasing them to the atmosphere. By cooling these exhaust gases and reducing their volume before releasing them to the atmosphere, the audible report also is reduced to a fraction of its unmuffled value.

The Breaker

A proper combination of arc elongation, arc cooling, and arc movement has provided a circuit interrupter that satisfies all of the requirements and benefits of a high arc-resistance interrupter. Arc elongation is achieved by its movement in three planes to form a serpentine path. Arc cooling results by squeezing the arc between ceramic walls and moving it rapidly across these cooling surfaces. Arc movement is established and controlled by directing the circuit currents through multiple blowout coils designed to maintain a strong uniform magnetic-field transverse to the major plane of the arc chute. As accessories to this magnetic field, air boosters assist arc movement at light currents, and a muffler cools the exhaust gases of exceptionally high currents.

The development of an interrupter, however, does not mark the completion of a circuit-breaker design. Contacts, operating means, insulation, conductors, and accessories are all a vital part of the complete device. The magne-blast breaker, adapted for vertical lift metal-enclosed equipments, uses a heavy-duty solenoid mechanism to operate its contacts. These contacts use fine silver primaries to carry load currents with minimum loss and to carry the inrush currents of a heavy fault. As the breaker trips open the current is transferred to an intermediate contact in a parallel circuit. This intermediate contact handles the small arc that is established as the reactance of the first blowout coil is shunted into the circuit through the arc-resistant alloy arcing contacts. The final interrupting arc then is drawn when the arcing contacts part and is carried, by the moving arc contact, to the lower arc runner where a second blowout coil assists in moving the arc along the diverging arc runners and into the arc chute. As the arc travels along these runners, supplemental blowout coils are shunted into the circuit to extend the

magnetic field over the working area of the chute.

The circuit breaker is well insulated by using conventional compound bushings around the conducting studs and by enclosing each phase in a removable housing of insulation. This construction emphasizes accessibility with increased reliability. All operating parts may be exposed readily by removing these subassembled box barriers. The conventional construction of the operating mechanism, accessory devices, and general problems of application have profited by the experience of engineers responsible for the design of the many other varieties of power circuit breakers manufactured.

A complete line of these breakers rated from 50,000 kva to 500,000 kva for use in modern vertical lift metal-clad switchgear is shown in Figure 17. Figures 18A and 18B are two typical oscillograms of the 500,000-kva breaker interrupting in excess of 500,000 kva at 13,000 and 14,500 volts respectively and illustrating the marked reduction in the last loop of short-circuit current caused by the high arc resistance even at these voltages.

It is fortunate that this type of high-arc-resistance breaker conforms to the general pattern and size of correspondingly rated oil circuit breakers while it offers the advantages of no oil. Its application to the same type of metal-clad equipments which have proved their worth for oil circuit breakers is therefore comparatively simple.

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The Short-Circuit Characteristics of D-C Generators

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KNOWLEDGE of the short-circuit characteristics of d-c machines is an essential factor in the design of d-c electric systems having a large low-voltage machine capacity concentrated in a small area. This information is particularly important in the design of systems such as those encountered aboard ship where circuit breakers, fuses, relays, and other protective equipment must be so applied and co-ordinated as to provide a high degree of reliability and service continuity. Available information relative to d-c short-circuit currents has been limited to theoretical analyses based on formal solution of the differential equations of current flow and the machine inductance and resistance values. As a tool in the routine design of d-c systems, this information has not been adequate, particularly when estimates must be made of the effect of fault resistance, choice of machine construction, and so forth.

For some years, the design of a-c systems has been facilitated by the use of the transient and subtransient reactances and the corresponding time constants of synchronous machines. These constants, based on application of the theorem of constant flux linkages to the a-c machine, represent to practical accuracy the performance of that machine under rapidly varying conditions such as those existing during short circuits. Relatively simple tests can be made to determine the various reactance values for a particular machine and form a basis upon which machine and system design requirements may be developed. With the aid of this theory, it has been possible to conduct extensive calculations of short-circuit current flow on a-c systems under a wide variety of conditions of external resistance, external reactance, and so forth, without the formal differential equations which otherwise would be required. The availability of this theory has contributed in no small measure to the high standard of performance which has been obtained on a-c electric systems.

An analysis has been made of d-c machine characteristics with the purpose of deriving a group of machine constants similar to those now applied to a-c machines. It has been found that the effect of magnetic saturation is very large in the short-circuited d-c machine and must be taken into account if a useful analysis is to be made. However, this condition has not prevented derivation of a group of machine constants directly analogous to corresponding a-c machine constants which can be applied practically to d-c system design calculations. In addition, these constants provide a convenient method of describing the effect of series and compensating windings on d-c machine performance. It is the purpose of this paper to describe this analysis. Although the calculation and application of machine constants is illustrated for the particular case of a 60-kw 250-volt shunt wound generator, tests have shown the theory to be applicable to machines of other types and sizes.

Equations for the short-circuit current of a shunt wound d-c machine having negligible armature circuit inductance are derived from the differential equations of current flow in Appendix I. Similar equations are derived for the compound wound machine in Appendix II. The assumption of negligible armature inductance permits armature current to rise practically instantaneously, thereby making the theorem of constant flux linkages applicable. Inasmuch as this theorem is understood more readily than the differential equations and furnishes a useful physical interpretation of the machine constants, the results of the analysis will be described in terms of constant flux linkages.

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Short Circuit of the Shunt Wound D-C Machine

Curves of armature and field current taken from an oscillogram of short circuit of a typical 60-kw 240-volt shunt wound d-c generator are shown in Figure 1. The construction of this machine is shown in Figure 2. The current changes following short circuit may be divided into two distinct periods: (1) a period of rapidly increasing armature and field current (*O-A*, Figure 1) and (2) a period of slowly decaying armature and field current (*A-B*, Figure 1). During the former period, total flux linkages in the shunt field winding are maintained nearly constant by current change in that winding, and the machine air-gap voltage changes only to the extent permitted by armature and field leakage flux. Current rise from zero to the peak value takes place at a rate determined by armature circuit inductance and the machine air-gap voltage. Shunt field current increases as required to maintain nearly constant the total effective shunt field flux linkages. The latter period consists of a slow current decay during which shunt field flux linkages, and consequently armature and field currents, are reduced from the value at the peak current point to the final steady short-circuit value. Current change during this period is so slow that armature circuit inductance has a negligible effect, and the rate of field and armature current decay is determined by the field circuit time constant corresponding to the peak value of field current attained.

It is evident from this discussion that the short-circuit characteristics of a d-c machine are closely analogous to those of an a-c machine. In each machine increased armature current associated with the short circuit has a demagnetizing effect on the field winding, which causes the field current to increase as required to maintain nearly constant the total effective field flux linkages. Likewise, after the peak value of armature current is reached (rms current in an a-c machine), the armature current decays to a steady state value at a rate determined by the field circuit time constant. Furthermore, the d-c machine of Figure 1 reaches a steady state short-circuit current value of

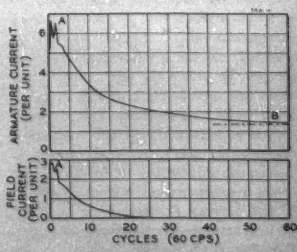


Figure 1. D-c short-circuit transient (no brush shift)

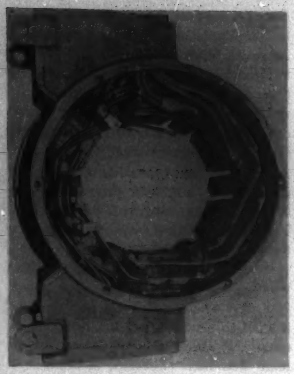


Figure 2. D-c machine typical of those tested

about 1.3 per unit, a value not greatly different from the steady state short-circuit currents encountered on a-c machines.

Magnetizing Effects

Analysis of magnetizing effects during short circuit of a d-c machine can be made most conveniently by considering the machine to have two sets of axes, as shown in Figure 3. The first set of axes, the direct and quadrature field axes, correspond to the actual field structure of the machine. Flux in the direct field axis links only the main field poles, whereas flux in the quadrature field axis links only the interpoles. Since the shunt field winding is on the direct field axis, the flux linkages maintained constant by that winding are the direct field axis flux linkages. The second set of axes, the brush axis and the quadrature brush axis, determines the actual generated voltage within the machine and the direction of armature magnetomotive force. Flux in the quadrature brush axis is effective in producing generated voltage, whereas flux in the brush axis gives no generated voltage. The magnetomotive force produced by the armature, however, is entirely along the brush axis. It is evident that when the brushes are located on the quadrature field axis (the so-called neutral axis), there is no distinction between the pole position and the brush position, and the two sets of axes coincide.

Figure 4 shows the steady state characteristics of a typical separately excited shunt wound d-c machine in terms of total field ampere turns, armature current, and quadrature-brush-axis air-gap flux. The latter quantity represents the machine flux in the quadrature brush axis, and hence the effective flux generating armature voltage. The machine terminal voltage in per unit equals the quadrature-brush-axis air-gap flux in per unit less the per unit voltage drop caused by machine resistance. In the case of a zero resistance fault, there can be no terminal voltage, and the per unit quadrature-brush-axis air-gap flux must equal the machine resistance drop in per unit. Operation therefore must be at some point along the machine *IR* drop line of Figure 4. Since armature inductance effects are negligible during the current decay period (*A-B*, Figure 1), the current changes during this period can be considered to follow the *IR* drop line of Figure 4 as a locus, the rate of motion being determined by the rate of shunt field current decay.

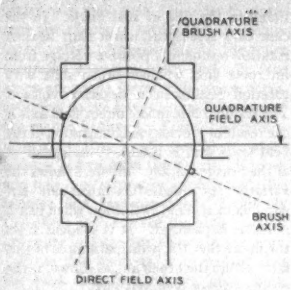


Figure 3. Magnetic structure of d-c machine

The curve of Figure 4 shows that with constant field current, quadrature-brush-axis air-gap flux decreases as armature current is increased. This change is caused by two demagnetizing components: (1) direct-field-axis armature magnetomotive force and (2) apparent direct-field-axis armature magnetomotive force associated with the quadrature-field-axis armature magnetomotive force. The first component is the result of actual direct-axis armature ampere turns and is proportional to the sine of the angle of brush displacement. The second component results from pole face and armature tooth saturation associated with cross flux from the quadrature axis armature magnetomotive force. As shown in Figure 5, the magnetomotive force added on one side of the main pole by quadrature-field-axis ampere turns is equal to that subtracted on the other side, but saturation causes the flux added to be less than the flux subtracted. Hence a lower value of average flux results. Tests show that, for the values of brush shift normally encountered in d-c machines, the effect of direct-field-axis armature ampere turns is small compared to the apparent magnetomotive force caused by the saturating effect of quadrature-field-axis armature ampere turns.

The effect of armature magnetomotive force just discussed is directly analogous to armature demagnetizing action in the a-c machine. There is one vital difference, however, for the armature demagnetizing action in an a-c machine is nearly proportional to the reactive component of armature current, whereas the armature

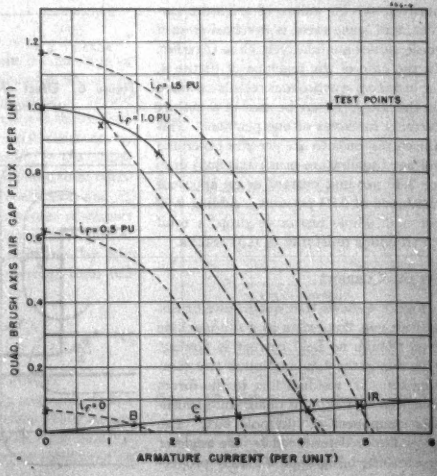


Figure 4. Steady state characteristics of a d-c machine (no brush shift)

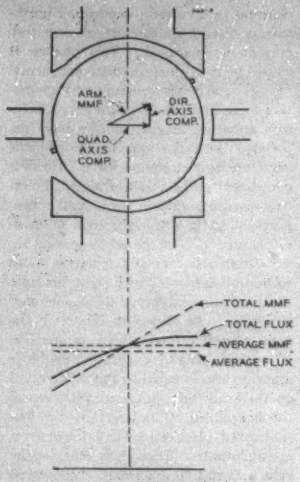


Figure 5. Armature demagnetizing effect in a d-c machine

demagnetization in a d-c machine largely results from magnetic saturation and is not directly proportional to armature current. In the a-c machine, the combined effect of reduced air-gap flux caused by demagnetization and internal voltage drop resulting from leakage reactance is lumped in the machine constant of synchronous reactance. A similar synchronous resistance may be used as a d-c machine characteristic. However, any single value of this resistance is effective only between specific values of armature current, and some error is involved even if these values are relatively close together. In the case of the machine of Figure 4, for instance, synchronous resistance based on the line X-Y may be used at armature currents in excess of one per unit. This line corresponds to one per unit generated voltage (quadrature-brush-axis flux) drop for 3.49 per unit current or an apparent resistance of 0.29 per unit. Adding 0.02 per unit ohmic resistance drop, a total synchronous resistance of 0.31 results.

Steady Current

Figure 4 shows that quadrature-brush-axis air-gap flux exists in a d-c machine even though no field current is flowing. This flux is the combination of two components: (1) residual flux in the direct field axis and (2) the quadrature-brush-axis component of interpole flux. The latter flux is determined by the angle of brush shift, being approximately proportional to the sine of that angle. In the case of a generator, brush shift against rotation results in a positive voltage from interpole flux, whereas brush shift with rotation results in a negative voltage. The residual flux in the direct field axis is the result of previous magnetization of the field poles and is relatively independent of the brush position. Figure 6 shows the variation in quadrature-brush-axis air-gap flux at no field excitation when brush position is changed. It is evident from the figure that the principal source of this flux, within the brush angles shown, is the residual direct-field-axis flux.

Peak Current

In passing from the condition of normal quadrature-brush-axis air-gap flux (Figure 4, point X) to the final short-circuit condition of 0.03 per unit quadrature-brush-axis air-gap flux (Figure 4, point B), the direct-field-axis flux is reduced substantially. In making this transition, however, there can be no instantaneous change in shunt field flux linkages as the infinite

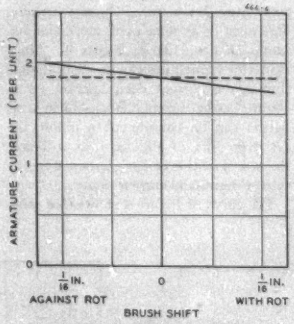


Figure 6. Effect of brush shift on steady state short-circuit current

voltages required to make such change are not available in the shunt field circuit. Accordingly, shunt field current rises to a value sufficient to give constant total flux linkages. At this point the flux linking the shunt field winding differs from the net quadrature-brush-axis air-gap flux by the field and armature leakage fluxes.

Figure 7 shows approximately the paths of armature and field flux components within a short-circuited d-c machine. Field flux consists of two components: (1) flux linking both the field and air gap, φ_{FA} (Figure 7), and (2) flux linking the field winding but not the air gap, φ_{FL}. Armature demagnetizing effects may be considered to produce two flux components, oppositely directed with respect to the main field flux. The first of these components, φ_A, links both the air-gap and the shunt field winding, whereas the second component, φ_{AL}, links only the air-gap. Since the armature leakage flux φ_{AL} does not link the field winding, it can change instantaneously. The combined effects of armature leakage flux and field leakage flux may be lumped in a total effective leakage coefficient which may be used to represent the over-all performance of the machine.

Figure 8 shows the results of a test to determine the magnitude of armature leakage flux. A short circuit was placed on the machine used in the test of Figure 1 and suddenly opened one-fifth second later. Since the shunt field flux linkages were nearly the same value after opening the short circuit as before, the value of terminal voltage following opening indicates the magnitude of armature leakage. The value of armature voltage during short circuit indicated in Figure 8 represents the actual quadrature-brush-axis flux computed from the product of arma-

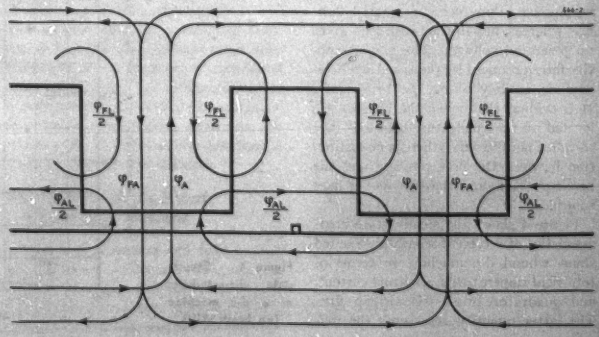


Figure 7. Basic flux paths in the d-c machine

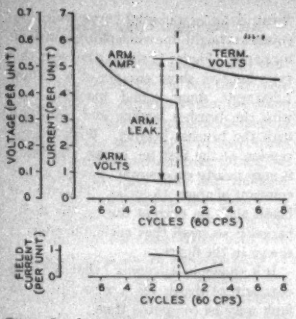
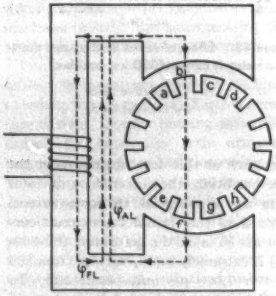


Figure 8. Interruption of a d-c short circuit

ture resistance and armature current. The field current before opening the fault was about 0.8 per unit, giving a value of φ_{FA} of 0.8 per unit (neglecting saturation). Since the net air-gap flux is equal to $\varphi_{FA}-\varphi_A-\varphi_{AL}$ (Figure 7) and is shown on the armature voltage curve to be 0.08, the sum of armature flux φ_A and armature leakage flux φ_{AL} is 0.72 per unit. The net shunt field flux is equal to $\varphi_{FA}+\varphi_{FL}-\varphi_A$ and is held constant by field current change. From the figure this value after opening the short circuit is 0.53 per unit. Assuming 0.2 per unit field leakage flux at one per unit field current, the field leakage flux component becomes 0.16 per unit at the 0.8 per unit field current prior to opening. Substituting this value of field leakage flux and field air-gap flux (0.8 per unit before the opening), the value of armature flux φ_A is 0.43 per unit. Since the sum of armature flux and armature leakage flux is 0.72 per unit, the value of armature leakage flux φ_{AL} is 0.29 and the armature leakage coefficient $[\pi_a=\varphi_{AL}/\varphi_A]$ is 0.67. Substituting this value of armature leakage flux and a value of 0.2 for the field leakage flux coefficient in equation 13, Appendix I, the value of apparent field leakage coefficient becomes unity.

Analysis of the cause of armature leakage flux in the d-c machine is complicated by the varying degrees of magnetic saturation existing throughout the magnetic circuit. However, a qualitative indication of the origin of this flux may be gained from consideration of Figure 9, which shows an equivalent electric circuit for the simplified magnetic structure of a 2-pole machine. In the figure batteries represent magnetomotive force values, and resistances represent reluctance. The two groups of four parallel resistance-battery combinations represent the four armature teeth assumed to be located under each main pole. In order to represent the effects of saturation, the reluctance values corresponding to the more saturated armature teeth and pole face areas are made larger than those corresponding to the less saturated portions of the magnetic circuit. From the figure it is evident that a substantial armature leakage flux exists in the circuit. If tooth and pole face saturation is neglected, this leakage flux becomes zero. Evidently this effect accounts for the high value of armature leakage flux shown in the tests.

From this analysis, it is evident that the peak armature current of a short-circuited d-c machine equals the value determined on the basis of synchronous resistance plus a current increment taking into account the increased field current required to maintain constant field flux



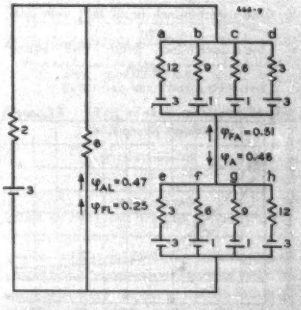


Figure 9. Equivalent magnetic circuit of a d-c machine

linkages. This current may be computed directly by regarding the d-c machine as having a transient resistance similar to direct axis transient reactance of an a-c machine. In Appendix I it is shown that the value of this transient resistance is $R_A+(\pi/1+\pi)R_s$, where R_A is the armature ohmic resistance, π is the total effective field leakage flux coefficient, and R_s is the equivalent armature resistance corresponding to the line X-Y, Figure 4. Designating transient resistance by R'_s, the peak short-circuit current from full voltage, full load is

$$i_{peak}=\frac{1+R'_s}{R_s+R'_s}\text{ per unit} \qquad (1)$$

where R_s is the fault resistance.

Equation 1 is directly analogous to the equation of peak transient short-circuit current for an a-c machine. The numerator of the equation can be considered to represent the voltage behind the transient resistance or the flux remaining constant during the short-circuit interval. In the case of the a-c machine, this flux actually exists across the air gap, whereas in the case of the d-c machine it is a purely fictitious flux since equation 1 is derived on the basis that armature demagnetizing effect does not commence until armature current reaches one per unit. The denominator of equation 1 represents the total effective circuit resistance retarding short-circuit current flow.

As shown in Figure 4, a reasonably accurate approximation of the demagnetizing effect of armature current in a d-c machine may be made by neglecting all armature demagnetizing effects for armature currents less than one per unit. Equation 1 is derived on this basis with

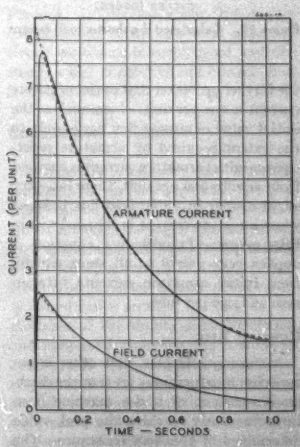


Figure 10. Effect of neglecting armature inductance

———Including armature inductance
– – – –Neglecting armature inductance

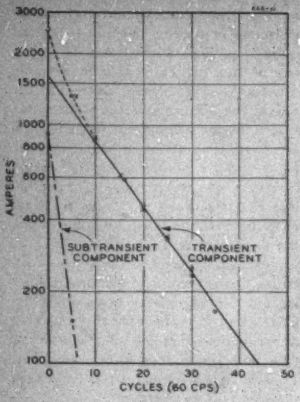


Figure 11. Current decay in d-c machine

o—One-sixteenth-inch brush shift with rotation

x—One-sixteenth-inch brush shift against rotation

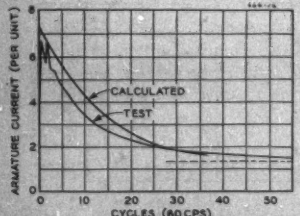


Figure 12. Calculated d-c short-circuit current

the further provision that initial armature current is one per unit. Inasmuch as the initial value of air-gap flux varies only to the extent required by armature resistance as initial armature current is changed from zero to one per unit, there is a very slight change in initial field flux linkages when armature current is changed within this range. Accordingly, equation 1 applies very nearly to all short circuits from initial armature currents between zero and one per unit.

Current Rise

Armature, interpole, and other armature circuit inductances prevent the short-circuit current of a d-c machine from instantaneously reaching the peak value determined by transient resistance. The character of this current rise is exponential if the armature demagnetizing effect behaves as a pure resistance and the armature circuit inductances do not saturate.

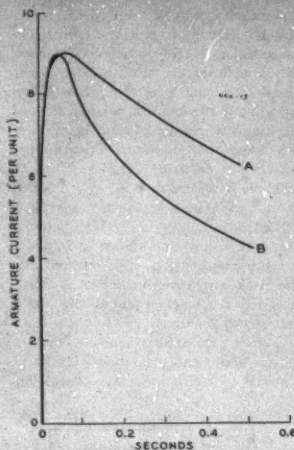


Figure 13. Effect of series field on d-c short-circuit current (300 kw machine)

A—Cumulative field

B—Differential field

Inasmuch as this does not represent the true condition, the current rise deviates from an exponential to some extent. Tests show that initial short-circuit current rise in small d-c generators (60–300-kw) is extremely rapid, varying from 500 to over 1,000 per unit per second. In fact, this current rise has been so rapid that it has been impossible to determine the exact shape of the current rise curve from test data.

Figure 10 shows the effect of the finite value of current rise on the calculated armature current following short circuit. The solid curve is the result of a computation based on the assumptions of Appendix I, but taking into account armature and interpole inductance. It was assumed in this calculation that armature circuit inductance gave an initial current rise of 800 per unit per second. From the figure it is evident that the curves correspond in all respects, except for the peak value and rate of rise of armature and field current. In the peak values, an error of eight per cent is involved, a small error in view of the approximations used in the analysis.

Current Decay

Armature current decays from the value associated with transient resistance to the final steady value at a rate dependent on the field circuit time constant of the machine. In the absence of saturation, this decay is an exponential curve which becomes a straight line when plotted on semi-log paper. Figure 11 shows a curve of this type for two short circuits of a 100-kw 1,200-rpm shunt-wound machine, one with the brushes leading and the other with the brushes lagging. With the exception of the first ten cycles, the decay is very nearly exponential, having a time constant of about 15 cycles. The effect of brush shift on current during the decay period is so small that negligible effect is shown in the figure.

It is shown in Appendix I that the time constant of decay for a zero resistance fault may be computed from

$$T = \frac{R'}{R_s} T_{FO} \qquad (2)$$

where T_{FO} is the field time constant at full load, full voltage and R_s the synchronous resistance. This relation is directly analogous to the equation for the transient short-circuit time constant of an a-c machine.

Subtransient Effects

Figure 11 is typical of several tests which have shown that current during the first few cycles following short circuit of a d-c machine exceeds the value based on transient resistance. This evidently is the effect of pole iron, bolts, welded sections, and so forth, in maintaining flux for a short period of time, thus giving the d-c machine a subtransient resistance analogous to the subtransient reactance of an a-c machine. From Figure 11 the approximate value of this resistance is 12 per cent and the time constant three cycles (0.05 second). These values are consistent with subtransient reactance and time constant valucs encountered on a-c machines of similar size.

Accuracy

To check the above theory, a calculation has been made of the transient short-circuit armature current of the machine used to obtain the data of Figures 1, 4, 8, and the equations of Appendix I. Values of synchronous resistance, effective field leakage coefficient, and open-circuit transient-time constant were taken as 0.31 per unit, 1, and 0.5 second respectively. The corresponding transient resistance is 0.16 per unit. Armature resistance was assumed to be 0.02 per unit. The results of the calculation are shown in Figure 12. It is evident that the computation checks in order of magnitude the actual short-circuit current transient obtained, all that can be expected in view of the assumptions used in deriving the equations of the appendix.

Compounding and Compensation

Figure 13 shows the short-circuit current of a d-c generator for two series field connections, one cumulative and the other differential. The peak armature current is practically the same value in each case, for the shunt field current maintained the same value of total field flux linkages nearly constant during the period of current buildup. That is the same air-gap flux, and therefore shunt field flux linkages, existed in the machine prior to each short circuit, and the same increase in total field magnetomotive force was required to maintain constant these flux linkages. Since the maximum value of total field magnetomotive force is the same in each case, the peak short-circuit currents are identical. However, the rate of current decay following the peak current value for the differential field connection is greater than for the cumulative field connection because the shunt field current required to maintain constant shunt field flux linkages in the former case is substantially greater than in the latter. This condition results because of the influence of the series field in supplying field magnetomotive force, aiding the shunt field in the cumulative wound machine, and opposing the shunt field magnetomotive force in the differential wound machine.

In addition to determining the rate of decay following peak short-circuit current, the presence of a series field alters the steady state short-circuit current value. The magnitude of this effect may be estimated from the curves shown in Figure 8 If a cumulative series field gives 0.1 per unit magnetomotive force at full load, for instance, there will be an added contribution of 0.1 per unit field magnetomotive force for every one per unit armature current. Hence for the case of Figure 4, point *B* will be moved along the line *IR* until the total field magnetomotive force in per unit corresponds to ten per cent of the armature current value, thereby placing point *B* in a position corresponding to 2.4 per unit armature current (point *C*, Figure 4).

The short-circuit curves of Figure 13 are based on two series field connections for a particular generator. If a machine is designed to give a particular value of voltage regulation, the series field winding may be used in lieu of other design changes to achieve this regulation. In particular, a large value of synchronous resistance may be used with a relatively strong cumulative series field to give the same voltage regulation as with a low synchronous resistance and no series field.

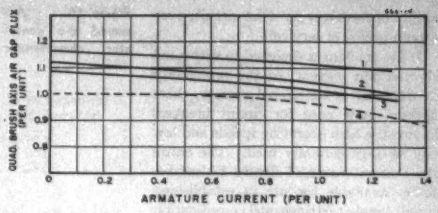


Figure 14. Steady state characteristic of compensated generators (no brush shift)

Curves 1, 2, and 3—1,100 kw 416-volt compensated generators

Curve 4—60-kw 240-volt uncompensated generator

In this case a smaller peak armature current on short circuit will be obtained than with the machine designed to achieve the same voltage regulation with only a shunt field winding. Tests show, however, that this effect is small with machines of 60 to 300 kw capacity, and that these machines have substantially the same peak short-circuit current, whether designed as shunt machines or series machines meeting the same voltage regulation requirements.

Compensating windings are provided in the pole face structure of d-c machines to reduce the magnetizing effects of armature current, thereby limiting saturation caused by quadrature axis armature magnetomotive force and decreasing the value of machine synchronous resistance. A corresponding reduction in transient resistance can be expected. If the compensation secured is perfect, the demagnetizing effects of armature current are reduced to zero and, with the brushes on the neutral axis, the short-circuit current will rise to a value limited only by armature resistance. On large machines this value may exceed 50 times normal current. Actually it does not appear that currents of this magnitude are to be expected, for actual compensation falls far short of the theoretically perfect compensating winding. This condition is evident in Figure 14 which shows a plot of the variation of quadrature-brush-axis air-gap flux with armature current for three 1,100-kw 416-volt compensated generators. By comparison with the curve of the machine of Figure 4, it appears that these particular compensated machines probably have synchronous resistance values comparable to the uncompensated machine of Figure 4.

Fault Resistance

The influence of fault resistance on peak short-circuit current of a d-c generator may be calculated from equation 1. A plot of calculated peak short-circuit current as a function of fault resistance for a particular machine is shown in Figure 15. The two test points indicate that the relation of equation 1 gives approximately correct results.

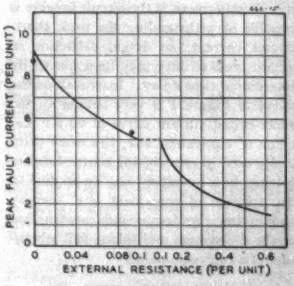


Figure 15. Effect of fault resistance on d-c short-circuit current

●—Test points

The influence of fault resistance on steady state short-circuit current may be estimated from the steady state machine short-circuit characteristics shown in Figure 4. In this case, a new *IR* drop line corresponding to the new total armature circuit resistance is constructed and the steady value of short-circuit current read from that curve.

Commutator Flashover

It generally is assumed that commutator flashover on short-circuited d-c machines can be prevented only by the use of circuit breakers having a combination of high operating speed and low trip setting which prevents buildup of armature current to the full short-circuit current value. A considerable number of tests on d-c machines of the shunt, stabilized shunt, and compound types varying from 60 to 300 kw, 240 volts, and having peak currents from 6 to 11 per unit have failed to produce a flashover. Although the tests were made under controlled conditions, they are considered to show that the probability of flashover has been exaggerated somewhat. In fact, it appears that generators in this range may be constructed economically to have a relatively low prob-

ability of flashover on short circuit, even after a period of service.

If the machine is designed to withstand short-circuit current, or the probability of flashover is considered remote, there appears little need for circuit breakers having the high operating speeds and low trip settings normally used. The entire short-circuit curve of Figure 1 then becomes available for use in establishing circuit-breaker settings, and co-ordination of circuit breakers may be obtained readily. Furthermore, if the circuit breaker is capable of withstanding the peak short-circuit current, an actual reduction in circuit-breaker duty may be achieved by intentional time delay. Inasmuch as the curve of Figure 1 is very similar to the short-circuit-current curve of an a-c machine of equivalent size, the same principles used in establishing circuit breaker settings in a-c systems may be applied to d-c systems of equivalent size, thereby simplifying the design and construction of the d-c system and taking full advantage of a-c developments.

Conclusions

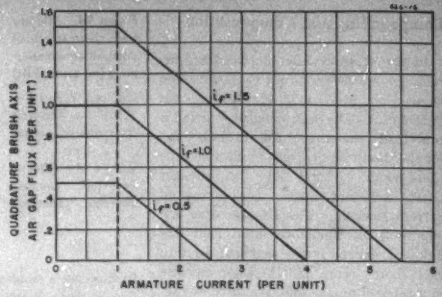
Calculations of the short-circuit current of d-c machines may be conducted by the use of machine constants of synchronous resistance, transient resistance, subtransient resistance, and the corresponding time constants. These values are directly analogous to the constants which have been applied to a-c machine calculations. The principal difference between the application of these constants to a d-c machine and the application of analogous constants to an a-c machine lies in the necessarily approximate method which must be used to represent the effect of machine saturation. This approximation does not, however, prevent reaching useful results.

The value of transient resistance for d-c machines is influenced to a considerable degree by the high value of armature leakage flux. This flux, apparently caused by the saturating effect of flux in the armature teeth, has given armature leakage flux coefficients of the order of 0.7 and corresponding total apparent field leakage flux coefficients of unity. These high values, as compared with the effective field leakage flux coefficient of from 0.2 to 0.4 on a-c machines, constitute an important distinction between the performance of the two types of machines under transient conditions.

The presence of a compound field winding has no influence on the peak value of short-circuit current attained by a d-c machine. However, a winding of this type is of considerable importance in determining the rate of armature current decay from the peak to the final steady value and the value of the final steady current reached. Compensating windings, which theoretically should result in extremely high values of transient resistance, do not appear sufficiently effective to produce this result, and there is little reason to believe that the high values of short-circuit current sometimes assigned to these machines actually will be reached. Further test data on these machines, however, will be required before definite conclusions can be reached.

In the case of small d-c machines, the probability of commutator flashover under short circuit appears to be somewhat exaggerated, and it is believed possible to establish circuit-breaker settings taking advantage of the probability that flashover will not occur. In this case the effective short current transient is very similar to that of equivalent a-c machine, and the methods developed for the design of a-c systems may be applied.

Figure 16. Assumed d-c generator characteristic



Appendix I. Short Circuit of a Shunt Machine—Mathematical Analysis

This analysis is based on the following assumptions:

1. Generated voltage (quadrature-brush-axis air-gap flux) may be represented by the following two components:

(a). A positive component proportional to field current, representing the magnetizing effect of field magnetomotive force.

(b). A negative component proportional to the excess of armature current over full load armature current, representing the demagnetizing effect of armature magnetomotive force (including saturation of the pole faces caused by quadrature axis flux).

This assumption amounts to representing the machine characteristics by the straight lines in Figure 16.

2. Field current (in amperes) is negligible as compared with armature current (in amperes).

3. The short circuit takes place from an initial condition of rated armature current and rated voltage.

4. Armature and interpole inductance is negligible. From Figure 10 it is evident that no significant error in peak current or current during the decay period results from this assumption.

Subject to these assumptions, the machine circuit equations may be written:

$$E_t = i_f - R_s(i_a - i_t) - R_a i_a \tag{3}$$

$$E_t = R_f i_f + L_f \frac{di_f}{dt} - M\frac{d}{dt}(i_a - i_t) \tag{4}$$

$$E_t = R_z i_a \tag{5}$$

where

E_t = terminal voltage in per unit

i_f = field current in per unit (based on the field current for rated armature voltage at no load)

R_a = armature ohmic resistance in per unit

i_a = armature current in per unit

R_s = equivalent armature resistance corresponding to the demagnetizing effect of armature current in per unit

i_t = current value above which R_s is measured in per unit (one per unit this analysis)

R_f = field resistance in per unit (based on the units of i_f and E_t)

L_f = field inductance in per unit (per unit field voltage induced by one per unit field current change per second)

M = coefficient of mutual inductance representing the shunt field voltage in per unit corresponding to one per unit armature current change per second

R_z = short-circuit resistance

It is convenient to base the calculation of M on the conventional system of units. Then

$$M_A = \frac{N_f \varphi_f}{i_a} \cdot 10^{-8} \tag{6}$$

where

M_A = value of M in henries

i_A = armature current change in amperes required to produce a change in shunt field flux linkages of $N_f \varphi_f$ maxwell turns

From Figure 16 it is evident that an armature current increase (above one per unit) equal to $1/R_s$ per unit causes the quadrature-axis air-gap flux to be reduced one per unit. The corresponding change in shunt field flux linkages can be shown to be $1/1+n_a$ per unit, where n_a is the ratio φ_{AL}/φ_A (Figure 7). Inasmuch as $1/R_s$ per unit current change produces $1/1+n_a$ per unit change in shunt field flux linkages, the current change required to make a one per unit change in shunt field flux linkages is $(1+n_a)/R_s$.

It is convenient to use as a basis of substitution in equation 6 the shunt field flux linkages upon which the shunt field inductance at no load, full voltage, is based. This value of flux is one per unit plus the shunt field leakage flux. If the shunt field leakage coefficient n_f is equal to $\varphi_{FL}/\varphi_{FA}$ (Figure 6), the shunt field flux at no load, full voltage is $(1+n_f)$ per unit. Since armature current must change $(1+n_a)/R_s$ per unit to give a one per unit change in shunt field flux linkages, an armature current change of $(1+n_a)(1+n_f)/R_s$ per unit is required to give a shunt field flux linkage change corresponding to the value of shunt field flux linkages at no load, full voltage. The value of this current in amperes is

$$i_A=\frac{i_{Au}(1+n_a)(1+n_f)}{R_s} \tag{7}$$

where i_{Au} is the rated armature current in amperes.

The value of $N_f\varphi_f$ at no load, full voltage is the value upon which the open circuit field time constant is based. If L_f is the shunt field circuit inductance (in henries) corresponding to this time constant, the value of $N_f\varphi_f$ is

$$N_f\varphi_f=L_fi_{fu}\cdot 10^8 \tag{8}$$

where i_{fu} is the shunt field current in amperes at no load, full voltage (base field current).

Then

$$M_A=\frac{L_fR_si_{fu}}{(1+n_a)(1+n_f)i_{au}} \tag{9}$$

The values of M_A and L_f in per unit notation are

$$M=\frac{M_Ai_{Au}}{V} \tag{10}$$

$$L_f=\frac{L_fi_{fu}}{V} \tag{11}$$

where V is rated armature voltage. Hence

$$M=\frac{L_fR_s}{(1+n_a)(1+n_f)} \tag{12}$$

It is convenient to consider the operation of the machine in terms of an equivalent shunt field leakage coefficient which combines the effects of field and armature leakage. This leakage coefficient may be defined by

$$(1+n)=(1+n_a)(1+n_f)$$

or

$$n=(1+n_a)(1+n_f)-1 \tag{13}$$

For small values of n_a and n_f, the value of n is nearly equal to n_a+n_f. Then

$$M=\frac{L_fR_s}{1+n} \tag{14}$$

Substituting equation 13 in equations 3, 4, and 5 and eliminating, it follows that

$$\left.\begin{aligned}-i_f+(R_a+R_x+R_s)i_a&=R_si_1\\ R_fi_f+L_f\frac{di_f}{dt}-R_si_a-\frac{L_fR_s}{1+n}\frac{di_a}{dt}&=0\end{aligned}\right\} \tag{15}$$

The Laplace transform of equation 15 is[4]

$$\left.\begin{aligned}-i_f(s)+(R_a+R_s+R_x)i_a(s)&=\frac{R_si_1}{s}\\ (R_f+L_fs)i_f(s)-\left[R_s+\frac{L_fR_s}{1+n}s\right]i_a(s)&\\ =L_fi_{fo}-\frac{L_fR_s}{1+n}i_{ao}&\end{aligned}\right\} \tag{16}$$

where i_{fo} and i_{ao} are the initial field and armature current, respectively, and T_o is the open circuit time constant of the field circuit.

Assuming the fault to take place from an initial condition of full voltage, full load, the constants of equation 15 become

$$R_f=\frac{1}{1+R_a},\ i_{fo}=1+R_a,\ L_f=T_o,\ i_{ao}=1$$

The value of i_1 has been taken previously as one per unit and therefore

$$\left.\begin{aligned}-i_f(s)+(R_a+R_s+R_s)i_a(s)&=\frac{R_s}{s}\\ \left[\frac{1}{1+R_a}+T_os\right]i_f(s)-\left[R_s+\frac{T_oR_s s}{1+n}\right]\times&\\ i_a(s)=T_o(1+R_a)-\frac{T_oR_s}{1+n}&\end{aligned}\right\} \tag{17}$$

Solving

$$\left.\begin{aligned}i_a(s)&=\frac{1}{sD}\left[\frac{R_s}{1+R_a}+sT_o\left(1+R_a+R_s\frac{n}{1+n}\right)\right]\\ i_f(s)&=\frac{1}{sD}\left[R_xR_s+sT_o\left(1+R_a\right)\right.\\ &\left.(R_a+R_s+R_x)-\frac{R_s}{1+n}(R_x+R_a)\right)\Big]\\ D(s)&=\frac{R_a(1-R_x)+R_s}{1+R_a}+\\ &sT_o\left(R_a+R_x+R_s\frac{n}{1+n}\right)\end{aligned}\right\} \tag{18}$$

The inverse transformation of equation 17 gives

$$\left.\begin{aligned}i_a&=A+(B-A)\epsilon^{-t/\tau}\\ i_f&=C+(D-C)\epsilon^{-t/\tau}\end{aligned}\right\} \tag{19}$$

where

A = steady value of armature current
B = peak value of armature current
C = steady value of field current
D = peak value of field current
T = time constant of decay

and

$$A=\frac{R_s}{R_a(1-R_x)+R_s} \tag{20a}$$

$$B=\frac{1+R_a+R_s\frac{n}{1+n}}{R_a+R_x+R_s\frac{n}{1+n}} \tag{20b}$$

$$C=\frac{R_sR_x(1+R_a)}{[R_a(1-R_x)+R_s]} \tag{20c}$$

$$D=\frac{(R_s+R_a+R_x)(1+R_a)-(R_x+R_a)\frac{R_s}{1+n}}{R_a+R_x+\frac{n}{1+n}R_s} \tag{20d}$$

$$T=\frac{(R_a+R_x+\frac{n}{1+n}R_s)(1+R_a)T_o}{R_a(1-R_x)+R_s} \tag{20e}$$

The time constant equation 20e may be simplified to

$$T=T_o\frac{(R_s'+R_x)(1+R_a)}{R_s-R_aR_x} \tag{21}$$

where R_s is the synchronous resistance, and R_s' is the transient resistance. If full load field time constant $T_o(1+R_a)$ is designated T_{FO}, and fault resistance is negligible, then

$$T=T_{FO}\frac{R_s'}{R_s} \tag{22}$$

Appendix II. Short Circuit of Compound Machine

In the series machine, armature current contributes to direct axis magnetomotive force. If the ratio of series field magnetomotive force to shunt field magnetomotive force at full load is k, then equations 3, 4, and 5 become

$$E_1=(i_f+ki_a)-R_si_a-R_s(i_a-i_1) \tag{23}$$

$$E_1=R_fi_f+L_f\frac{di_f}{dt}-M\frac{d}{dt}(i_a-i_1) \tag{24}$$

$$E_1=R_xi_a \tag{25}$$

In addition to this change, the value of M must be altered to take into account the increased mutual inductance associated with the presence of the series field. The total mutual inductance can be considered as comprising two components: (1) that resulting from R_s and (2) that resulting from the series field. From equation 14 the mutual inductance attributable to R_s is $(L_fR_s)/(1+n)$. From a similar derivation, using the series field current required to produce a change in shunt field flux linkages equal to the no load full voltage linkages, it can be shown that the series field contribution to mutual inductance is $-L_fk$ (neglecting leakage flux between the shunt and series fields). The value of M then becomes $L_f[(R_s/1+n)-k]$.

In the compound wound machine, the initial value of field current must reflect the series field magnetomotive force contribution. For full voltage, full load, the shunt field current is $(1+R_a-k)$ per unit and the corresponding field resistance is $1/(1+R_a-k)$ per unit.

Substituting and solving as in the case of

shunt machine, the constants A, B, C, D, and T of equation 18 become

$$\left.\begin{aligned}
A &= \frac{R_s}{(R_a-k)(1-R_x)+R_s} \\
B &= \frac{1+R_x+R_s\dfrac{n}{1+n}}{R_x+R_a+\dfrac{n}{1+n}R_s} \\
C &= \frac{R_xR_s(1+R_a-k)}{(R_a-k)(1+R_x)+R_s} \\
D &= \frac{\left[(R_a+R_s+R_x-k)(1-R_x)-\dfrac{R_s}{1+n}(R_a+R_x+kn)\right]}{R_x+R_a+R_s\dfrac{n}{1+n}} \\
T &= \frac{\left(R_x+R_a+\dfrac{n}{1+n}R_s\right)(1+R_a-k)}{(R_a-k)(1-R_x)+R_s}T_o
\end{aligned}\right\} \quad (26)$$

The peak armature current obtained by use of the values of equation 23 is

$$\frac{1+R_a+\dfrac{n}{1+n}R_s}{R_x+R_a+R_s\dfrac{n}{1+n}}$$

or the same value as obtained from the values for the shunt machine given in equation 19.

Appendix III

The equations derived in Appendix I and Appendix II disregard effects of residual flux, saturation, and armature inductance. It is convenient to have empirical relations taking these effects into account. These relations can be obtained by using the peak current values and time constants from Appendix II and the initial rate of rise and final steady current from other data. The complete equation for armature current then becomes

$$i_a = I_s + (I_p - I_s)\epsilon^{-t/T} - I_p\epsilon^{-t/\tau} \quad (27)$$

where

I_s = steady current value following short circuit

I_p = peak current value following short circuit from equation 26,

$$\left[\frac{1+R_a+R_s\dfrac{n}{1+n}}{R_x+R_a+R_s\dfrac{n}{1+n}}\right]$$

T = time constant of current decay from equation 26

$$\frac{\left(R_x+R_a+\dfrac{n}{1+n}R_s\right)(1+R_a-k)}{(R_a-k)(1-R_x)+R_s}T_o$$

T = time constant corresponding to the initial rate of current rise. If i' is the initial rate of current rise in per unit per second, then $T = \dfrac{I_p - I_s}{i'}$

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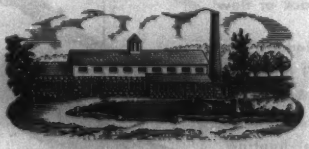

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		R	RH	RW	RU	T (Formerly SN)	TW
Maximum Operating Temperature	1940	60 C	75 C	60 C	60 C	60 C	
	1946	60 C	75 C	60 C	60 C	60 C	60 C
Insulation Wall Thickness	1940	2/64"—#14, 12, 10 AWG 4/64"—#8—2 AWG 5/64"—#1—4/0 AWG	2/64"—#14, 12, 10 AWG 4/64"—#8—2 AWG 5/64"—#1—4/0 AWG	2/64"—#14, 12, 10 AWG 4/64"—#8—2 AWG 5/64"—#1—4/0 AWG	18 Mils (1.18/64) #14, 12, 10 AWG	2/64"—#14, 12, 10 AWG 3/64"—#8 AWG 4/64"—#8—2 AWG 5/64"—#1—4/0 AWG	
	1946	2/64"—#14, 12 AWG 3/64"—#10 AWG 4/64"—#8—2 AWG 5/64"—#1—4/0 AWG	2/64"—#14, 12 AWG 3/64"—#10 AWG 4/64"—#8—2 AWG 5/64"—#1—4/0 AWG	2/64"—#14, 12, 10 AWG 4/64"—#8—2 AWG 5/64"—#1—4/0 AWG	18 Mils (1.18/64) #14, 12, 10 AWG 25 Mils (1.6/64) #8, 6 AWG	2/64"—#14, 12, 10 AWG 3/64"—#8 AWG 4/64"—#8—2 AWG 5/64"—#1—4/0 AWG	2/64"—#14, 12, 10 AWG 3/64"—#8 AWG 4/64"—#8—2 AWG 5/64"—#1—4/0 AWG
Uses (Under National Electrical Code)	1940	General Use	General Use	General Use or In Wet Locations	Rewiring Only	Rewiring Only	
	1946	General Use	General Use	General Use or In Wet Locations	General Use May be used in Non-Metallic Sheathed Cable	#14—4/0 AWG General #14—2000 MCM Open Work	#14—4/0 AWG General #14—2000 MCM Open Work
Sizes (Under National Electrical Code)	1940	#14—2000 MCM	#14—2000 MCM	#14—2000 MCM	#14, 12, 10 AWG	#14—4/0 AWG	
	1946	#14—2000 MCM	#14—2000 MCM	#14—2000 MCM	Now Approved in Sizes #14—6 AWG	#14—4/0 AWG General #14—2000 MCM Open Work	#14—4/0 AWG General #14—2000 MCM Open Work

Current Carrying Capacity (In Amperes)

	Size	Conduit*	Open Wiring	Size	Conduit*	Open Wiring	Size	Conduit*	Open Wiring	Size	Conduit*	Open Wiring	Size	Conduit*	Open Wiring	Size	Conduit*	Open Wiring
1940	14	15	20	14	22	29	14	15		14	18		14	18				
	12	20	28	12	27	37	12	20		12	23		12	23				
	10	25	35	10	37	50	10	25		10	31		10	31				
	8	35	48	8	49	69	8	35					8	41				
	6	45	65	6	65	94	6	45					6	54				
	4	60	87	4	86	125	4	60					4	72				
	2	80	118	2	115	170	2	90					2	96				
1946	14	15	20	14	15	20	14	15	20	14	15	20	14	15	20	14	15	20
	12	20	25	12	20	25	12	20	25	12	20	25	12	20	25	12	20	25
	10	30	40	10	30	40	10	30	40	10	30	40	10	30	40	10	30	40
	8	40	55	8	45	65	8	40	55	8	40	55	8	40	55	8	40	55
	6	55	80	6	65	95	6	55	80	6	55	80	6	55	80	6	55	80
	4	70	105	4	85	125	4	70	105				4	70	105	4	70	105
	2	95	140	2	115	170	2	95	140				2	95	140	2	95	140

*Not more than 3 conductors in conduit, raceway or cable. For more than three conductors in conduit, raceway or cable, reduce current carrying capacity in accordance with 1946 Code.

Write for new wall hanger soon available. In meantime, use this chart

NOTE: According to Underwriters Laboratories; 1946 Code—R, RH and RW—may be labeled after April 1, 1946. Manufacturers need not produce until November 1. When production does start, Underwriters' labels must be applied and tags must be marked: "1946 Code."

1940 Code—R, RH, RW—may be labeled until November 1, 1946. Stocks in inventory after November 1 may be used until supply is exhausted.

Layflex (RU) is America's smallest diameter, lightest weight rubber insulated branch circuit wire. Laminated construction and perfectly centered conductors insure electrical safety.

UNITED STATES RUBBER COMPANY

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KEPT BOMBERS ON THE BEAM

● Plastics materials are so versatile that molding compounds can be developed to meet special conditions. Often the success of a plastics application depends upon the development of special molding compound.

An example is the Loop Antenna Housing manufactured by General Electric for bombers during the war. When early models were tested, they stood up under wind, rain, ice, sun, and extremes of temperature. But the plastics material used gave unforeseen trouble.

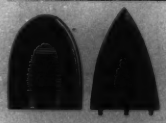
It released ammonia that corroded the metal fittings. And it did not give sufficient safeguard against the building up of static electricity. Too much static would interfere seriously with radio reception.

G-E engineers corrected the corrosion condition by replacing the two-stage phenolic resin with an ammonia-free one-stage resin in the molding compound.

Then it was found that the addition of graphite to the molding compound would give the degree of conductivity necessary to prevent hazardous static build-up in the molded plastics parts.

The fabric filler used in this ammonia-free, graphite-added molding compound were cuttings of fine cotton twill uniform shirts supplied by military tailors. These "shirttails" had to be carefully selected, because textile which had been waterproofed for tropical use failed to absorb resin.

This special molding compound made the plastics Loop Antenna Housing acceptable—and General Electric supplied tens of thousands of them for our bombers.



WHY G. E. USED "DEEP-THROAT" MOLDS FOR ANTENNA HOUSING. Cross-section split of teardrop design gave alignment to the two sections—facilitated their assembly—minimized shrinkage and warpage factors.

G. E. employs all available plastics materials in the development of molding compounds. That is why you can be sure of an unbiased material specification when you bring your plastics problem to General Electric—the world's largest manufacturer of finished plastics products. "*Designing Molded Plastics Parts*," *a helpful booklet, will be sent to you upon request.* Section E-4, Plastics Divisions, Chemical Department, General Electric Company, 1 Plastics Avenue, Pittsfield, Mass.

GENERAL ELECTRIC

EVERYTHING IN PLASTICS

Surer even than a pilot's eyes

. . . the high-frequency cable that makes **RADAR** *possible*

is insulated with

Du Pont POLYTHENE

CUT-BACK SECTION of a modern twin coaxial cable for use in direction-finding equipment at ultra-high frequencies (400 to 10,000 megacycles). JAN-C-17 designation RG-23/U; made by Anaconda Wire & Cable Co. The insulation, about 140-150 mils thick, is Du Pont polythene.

Radar and associated electronic developments, born in stress of war, have important peacetime uses immediately ahead. Ships and planes which, without radar, might be hopelessly lost in foul weather or fog, may now soon be located . . . come safely to harbor or airport . . . thanks to one or several of the four main types of radar.

In this important work Du Pont polythene plays an indispensable part. For radar depends on ultra-high frequencies —anywhere from 2 to 10,000 megacycles! The cables that carry these currents must have an insulating material of low electrical losses—which at the same time is flexible at low temperatures. *Du Pont polythene meets both these requirements.*

Other properties of Du Pont polythene: outstanding chemical inertness, light weight (specific gravity 0.92), low moisture permeability, flexibility in thin sections, rigidity in thick. For complete data sheet, write to E. I. du Pont de Nemours & Co. (Inc.), Plastics Dept., Room 166, Arlington, N. J.

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Miles of distribution lines cover the many acres of plant operations at the huge Grasselli, New Jersey works of this corporation. The first AmerTran installation went into service many years ago. It is on the job today, supported by many other AmerTrans throughout the property. These units range from the main power transformers down through the various ratings of distribution types—to the compact, troublefree, "at-the-load" dry type AmerTrans.

If continued buying means satisfaction, we'd say that AmerTrans are doing a pretty satisfactory job for this busy company. In fact, they told us so!

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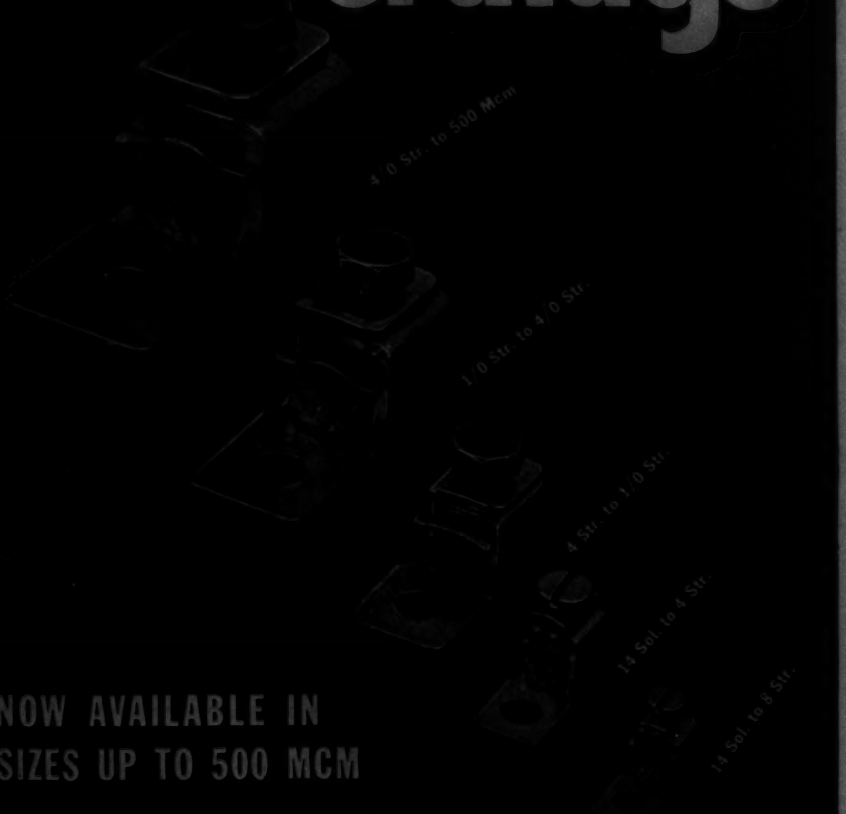

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THESE two portable, self-contained bridges are designed for use in the laboratory, in production testing and in industrial plants. Their accuracy is sufficient for a large majority of routine measurements. Their usefulness is increased considerably by their being portable, self-contained, battery operated, and complete and ready to use at all times. They are both housed in walnut cabinets with removable cover and are supplied with the 6-volt dry battery and headset required for each.

TYPE 1614-A CAPACITANCE BRIDGE

RANGE for Capacitance: 10 micromicrofarads to 100 microfarads in three steps; 10 micromicrofarads to 10,000 micromicrofarads; 0.01 microfarad to 1.0 microfarad and 1.0 microfarad to 100 microfarads. **ACCURACY:** ±2% except on lowest range where, after zero of 9 microfarads is subtracted, accuracy is ±2 microfarads +2% of dial reading. **DIAL CALIBRATION:** approximately logarithmic over two main decades, with compressed lower decade used for measurements below 100 microfarads. **RANGE** for Dissipation Factor: 0 to 45%. **FREQUENCY:** 1000 cycles ±5% from internal oscillator. **ACCESSORIES REQUIRED:** if a d-c polarizing voltage is used a 2 microfarad blocking condenser is required. Space is provided in the cabinet for such a condenser, not supplied with the instrument. **Price: $105.00**

TYPE 1631-A INDUCTANCE BRIDGE

RANGE for Inductance: 10 microhenries to 100 henries in 3 steps of 10 microhenries to 10,000 microhenries; 0.1 henry to 1 henry and 1 henry to 100 henries. **ACCURACY:** ±2.5% of dial reading between 100 microhenries and 10 henries. Below 100 microhenries the error varies inversely as the magnitude of the unknown. **DIAL CALIBRATION:** approximately logarithmic over two main decades with a compressed lower decade for measurements below 100 microhenries. **RANGE** for Q (storage factor): 1 to 45. Other specifications are the same as those for the Type 1614-A Capacitance Bridge. **Price: $115.00**

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THE difference between adaptability and *engineered* adaptability may add definite performance and cost advantages to your product. Consult with our engineers NOW if you plan to use production-run quantities of small motors (1/500 to 1/15 H.P.) in your 1947 products. A skilled experienced factory engineer will meet with your engineers in your own plant. He'll make a thorough study of your product design and probably recommend a motor of standard type. *But,* he'll *engineer* the physical and electrical characteristics of the motor—varying them to adapt the motor *specifically* to your product. Write today, describing briefly your product design plans.

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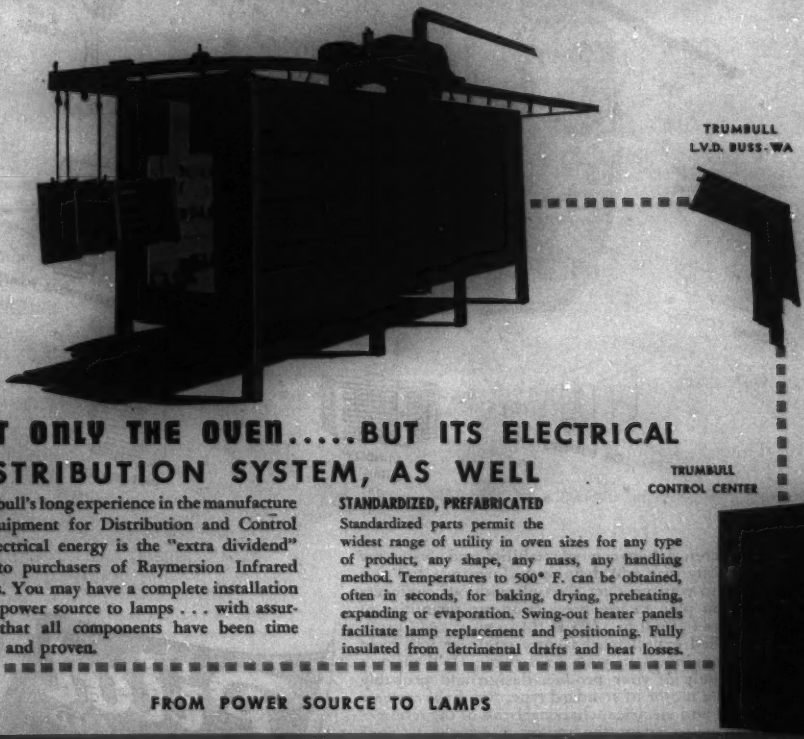
in any size



NOT ONLY THE OVEN.....BUT ITS ELECTRICAL DISTRIBUTION SYSTEM, AS WELL

Trumbull's long experience in the manufacture of equipment for Distribution and Control of Electrical energy is the "extra dividend" paid to purchasers of Raymersion Infrared Ovens. You may have a complete installation from power source to lamps . . . with assurance that all components have been time tested and proven.

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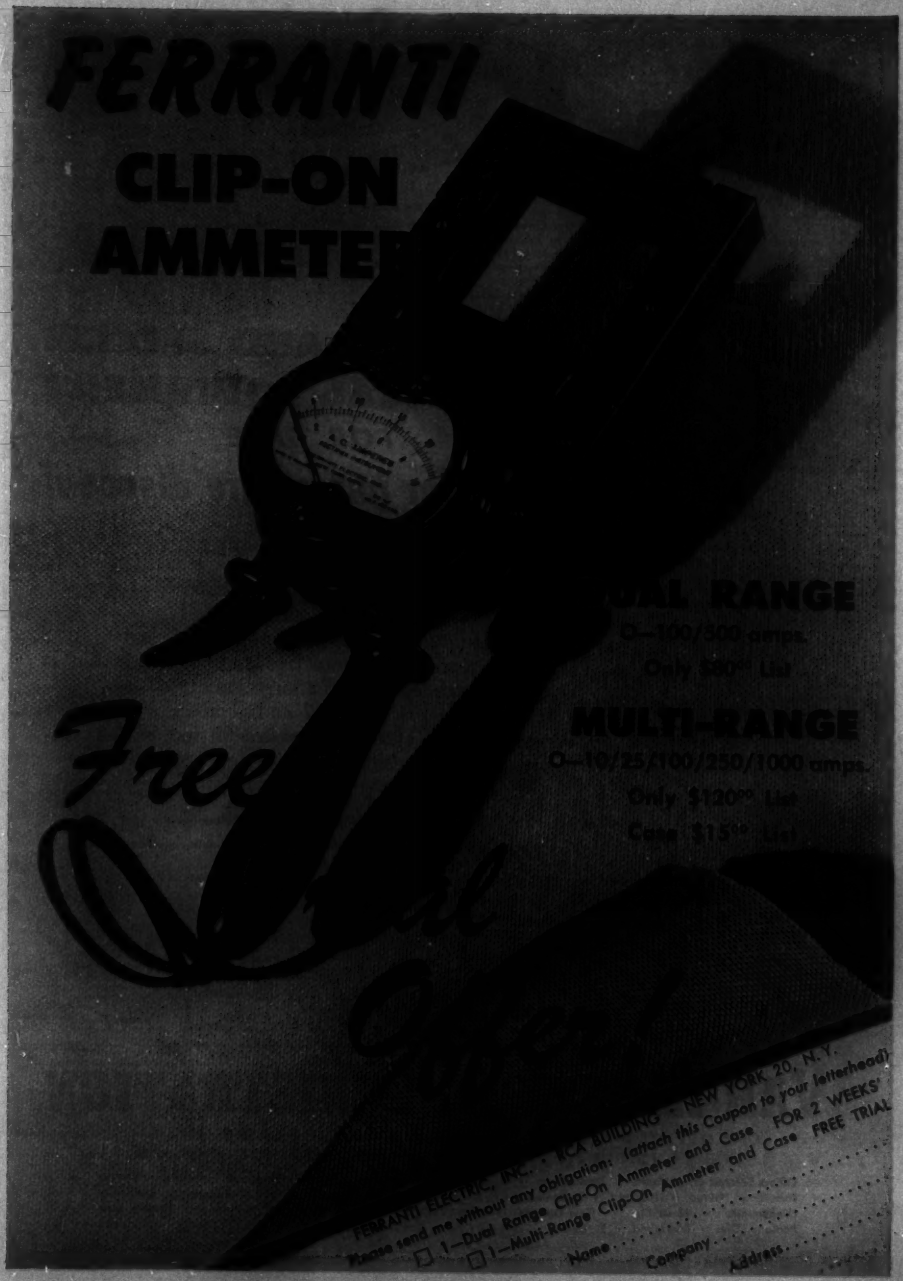
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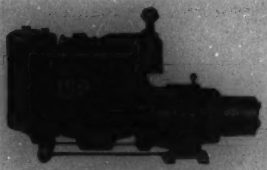

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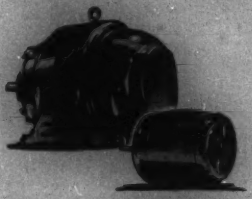
If unit power generation is your problem, it will pay you to check our large lists of this type of equipment. We have gasoline, steam, Diesel and electric driven generators—(and generators without prime movers) in a wide range of load and voltage characteristics, in both a-c and d-c.

WIRE & CABLE

Our inventory includes an innumerable variety of wire and cable in sizes and insulations usable in industry. Many types conform to underwriters' specifications—others were made for special purposes but are adaptable to industrial and commercial applications.



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We have a large supply of electric motors, both a-c and d-c, in unusual speeds, voltages and loads. If you have applications in which these motors can be adapted, inquire at your nearest Regional Office for full particulars and prices.

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FOR SALE

priced for immediate disposal

The War Assets Administration offers you government-owned surplus electrical machinery and equipment for your reconversion program at *substantially reduced prices.*

The offer includes wire and cable, generator sets, transformers, switch gear, wiring devices, sub-station power conversion and protective equipment. Much of it is special but adaptable to a large variety of uses.

It has been *priced to sell* and represents attractive bargains to the alert and resourceful industrialist engaging in speedy reconversion.

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OFFICES LISTED BELOW ARE TEMPORARILY IN RECONSTRUCTION FINANCE CORPORATION AGENCIES

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VETERANS OF WORLD WAR II: To help you purchase surplus property, a veterans' unit has been established in each WAA office.

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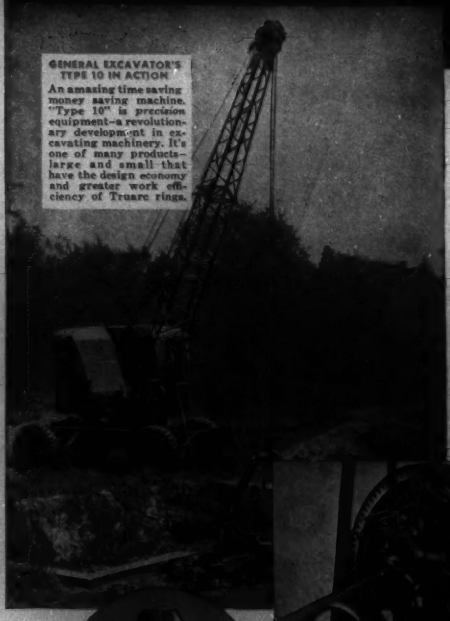

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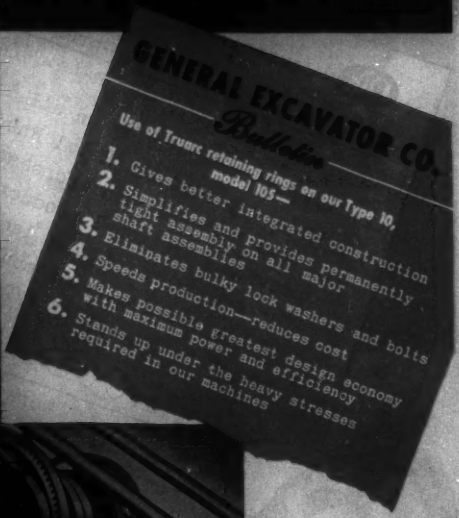
An amazing time saving money saving machine. "Type 10" is precision equipment—a revolutionary development in excavating machinery. It's one of many products—large and small—that have the design economy and greater work efficiency of Truarc rings.


GENERAL EXCAVATOR CO.
Bulletin
Use of Truarc retaining rings on our Type 10, model 105—
1. Gives better integrated construction
2. Simplifies and provides permanently light assembly on all major shaft assemblies
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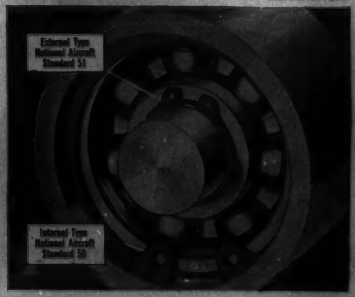
FREE! See how Truarc can improve your products—cut production and maintenance costs. Write today for Truarc booklet showing applications and design sketches. Specify Booklet 16C

NOW YOUR MACHINES CAN HAVE THE DESIGN ECONOMY of retaining rings regardless of load, stress or accuracy involved. Waldes TRUARC high precision retaining rings do the job of nuts, shoulders, collars, pins and snap rings. Yet they allow lighter, more compact units—make assembly and disassembly quicker, easier. TRUARC retaining rings give *better, more dependable retention* because their mathematical precision means perfect circularity—insures an unfailing grip. There's a Truarc ring for every mechanical purpose.



WALDES TRUARC RETAINING RINGS

TRADE MARK

WALDES KOHINOOR INC., LONG ISLAND CITY 1, N. Y.

Good News!...

INTER-OFFICE MEMO

To: Harry A. Ehle, Vice-pres., Sales
Date: 4/20/46

Production capacity on all types and ranges of All-Metal Rheostats has now been increased to provide additional production for scheduling during last week of May and following months, as per your request of 2/20/46.

From: O.J. Greenway
Works Manager

IRC

All Metal
RHEOSTATS

. . . Increased Quantities Now Available on Short Delivery Cycle!

PR-25

TYPE PR-25—25-watt rating. Temperature rise, 140°C. Standard resistance values, 1 ohm to 5,000 ohms. Diameter, 1⅜". Depth behind panel, 31/64".

PR-50

TYPE PR-50—50-watt rating. Temperature rise, 170°C. Standard resistance values, 0.5 ohm to 10,000 ohms. Diameter, 2⅜". Depth behind panel, 1¾".

TYPE PRT-25—(AN3155-25). 25-watt rating. Fulfills AN3155 specifications. Totally enclosed. Heat-radiating black finish. Rear terminals. Standard values, 10 ohms to 200 ohms. To 5,000 ohms on special order. Temp. rise, 140°C.

PRT (AN3155)

TYPE PRT-50—(AN3155-50). 50-watt rating. Same construction as PRT-25, to AN3155 specifications. Standard values, 5 ohms to 200 ohms. To 10,000 ohms on special order. Temp. rise, 170°C.

All IRC Rheostats operate at about half the temperature rise of equivalent units and can be operated at full load on as little as 25% of the winding with only a slight increase in temperature rise.

CONTACT YOUR IRC REPRESENTATIVE FOR COMPLETE DETAILS

IRC — PREFERRED FOR PERFORMANCE — FIXED & VARIABLE RESISTORS

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DU MONT'S *new* 5-INCH OSCILLOGRAPH

The Type 274

Designed to meet the demand for an inexpensive general-purpose instrument

COMPARES FREQUENCIES • ANALYZES PERFORMANCE • SHOWS CIRCUIT FUNCTIONS

In engineering the new Du Mont Type 274 Oscillograph, the emphasis has been on "quality at a price" —and not price alone. The result: the finest laboratory instrument ever offered for less than one hundred dollars. Available soon—and *it's worth waiting for!*

only $99.50

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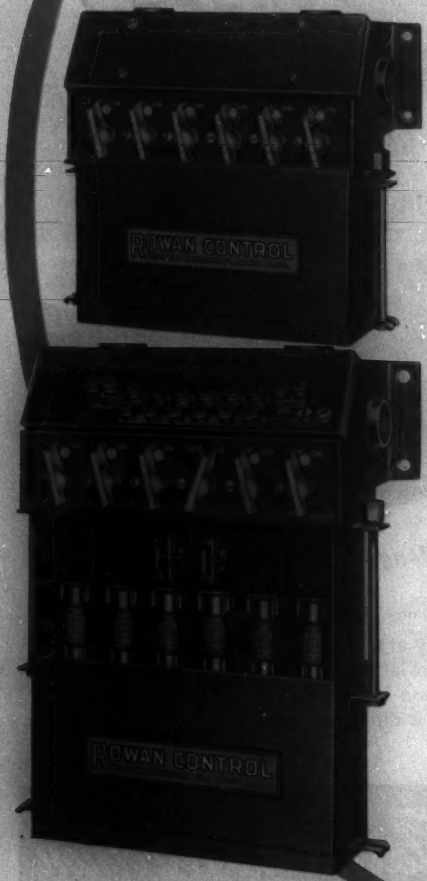
ALLEN B. DUMONT LABORATORIES, INC. PASSAIC, NEW JERSEY • CABLE ADDRESS, ALBEEDU PASSAIC N. J. U. S. A.

Announcing

THE NEW ROWAN OIL IMMERSED

TYPE 800

LIGHTING SWITCH



Industrial demand for a rugged Lighting Switch which provides safety, dependability, minimum maintenance and positive operation for use in locations where atmospheric conditions are adverse, has been met by Rowan engineers with the new type 800, oil immersed Lighting Switch. These switches are now available in 6- and 12-gang single circuit panels of 125/250 Volt A.C., 3 wire main.

Short circuit and overload protection is provided by use of the time-tested Rowan Air-seal fuses. All electrical operating parts are completely oil immersed thereby eliminating undue heating and oxidation of the fuse clips.

Accelerated tests of over 3,000,000 operations without failure assure you of dependable performance and minimum maintenance.

Descriptive circular available upon request.

Sectional view of the Rowan time-tested Air-seal fuse.

ROWAN CONTROL

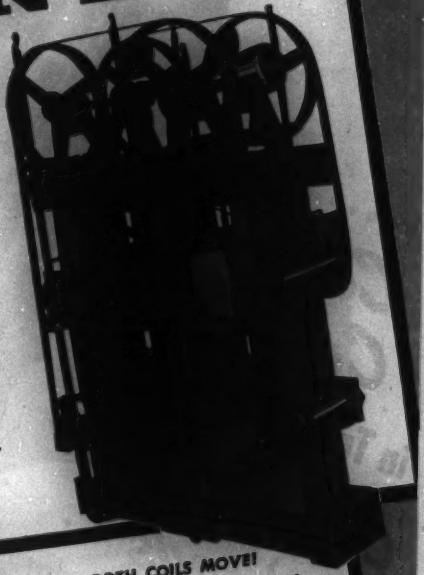
THE ROWAN CONTROLLER CO., BALTIMORE, MD.

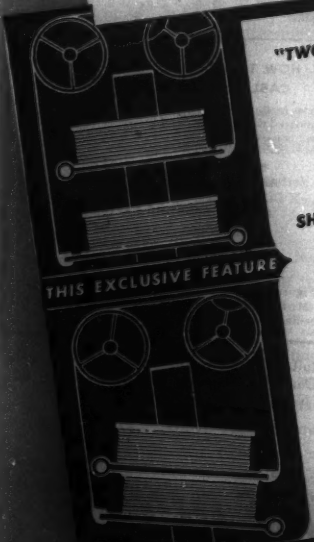
MOLONEY

Constant Current

TRANSFORMERS

For closer regulation through all ranges of load...less attention...lower maintenance cost! The superior features of Moloney Transformers coupled with soundness of mechanical design is your assurance of years of trouble-free service under the most severe operating conditions.





"TWO MOVING COIL" TYPE . . . BOTH COILS MOVE!

Upon changes in load or on primary surges, normal secondary current is more quickly attained because each coil moves only *half the distance* that the single coil would move on an ordinary regulator. Throughout the operation the coils are kept in parallel position thus securing closer regulation of secondary current.

SHORT CIRCUIT SHOCKS MINIMIZED!

Another feature of Moloney double-moving coil design is the lowered kinetic energy of the coils which practically eliminates force on the bumpers during a short circuit. By eliminating direct metallic contact between the core frames and tank, the usual transformer hum is practically eliminated. Moloney Constant Current Transformers give you these operating features: Automatic and instantaneous regulation . . . no taps or adjustments necessary to maintain constant current from full load to short circuit, when primary voltage is between 5% plus or minus of normal rated voltage.

External View, Type SLB Constant Current Transformer

MOLONEY ELECTRIC CO. ☆ ST. LOUIS 20, MO.

LEADING MANUFACTURER OF ALL INDUSTRIAL VOLTAGES

Cooler Cables in Transite Ducts Carry Heavier Loads

Increases of as much as 15% in current carrying capacity have been measured in cables sheathed in Transite Ducts!

The figures in the test case illustrated, made by Johns-Manville Research Engineers in collaboration with several leading cable engineers, apply to a single Transite Duct compared with an organic duct.

Transite Ducts have been proved to dissipate I^2R losses 13% faster than other ductways tested, thus keeping cables cooler. Higher load capacity, reduced copper losses and increased cable insulation life are the results.

Made of asbestos and cement, Transite Ducts are strong, immune to rust and rot. They are incombustible and unaffected by electrolysis or galvanic action. A permanently smooth bore makes possible long cable pulls and easy replacements. Long, lightweight lengths can be quickly and economically installed. In addition, a full line of fittings simplifies even the most complicated installations.

HOW TRANSITE DUCTS INCREASE CABLE CARRYING CAPACITIES

Tests made on a lead-sheathed 500,000 CM cable insulated with ½" paper and placed inside a single duct encased in concrete.

Sheath Temperature, 145° F.
Ambient Air Temperature, 90° F.

CURRENT CARRYING CAPACITY

Transite Duct	796 amperes
Organic Duct	691 amperes
Difference	105 amperes

(Figures are results of tests conducted in the J-M Laboratory in collaboration with several leading cable engineers.)

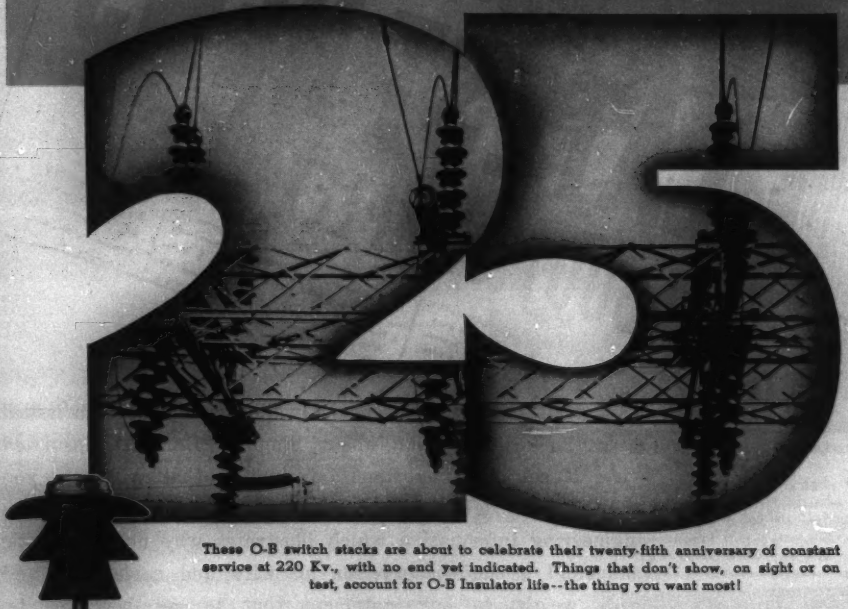
For full information on Transite Ducts, write for Data Book DS-410. Johns-Manville, Box 290, New York 16, New York.

Johns-Manville

TRANSITE DUCTS

CONDUIT for use without concrete
KORDUCT for concreting in

THE "SILVER ANNIVERSARY" OF A SOUND DECISION



These O-B switch stacks are about to celebrate their twenty-fifth anniversary of constant service at 220 Kv., with no end yet indicated. Things that don't show, on sight or on test, account for O-B Insulator life--the thing you want most!

All switch and bus insulators *look* pretty much alike, but they don't *act* alike! When new, there isn't much difference, but they don't stay new! It's one thing to meet standard specifications with a unit fresh from stock, but it's something entirely different to continue meeting every *service requirement* for a quarter-century or more, with the end nowhere in sight... Many thousands of O-B switch and bus insulators have passed their "Silver Anniversary" of faultless performance. The ruggedness that was there when they were new--but didn't show--has been paying dividends and will continue to do so for years to come... After all, isn't this what you *really want* in an insulator? Then buy O-B!

Ohio Brass

MANSFIELD, OHIO

CANADIAN OHIO BRASS CO., LTD., NIAGARA FALLS, ONT.

HEADQUARTERS FOR PORCELAIN INSULATION

2948-H

A New Data Sheet, richly illustrated, has been issued giving new information about Simplex-PLASTEX insulated wire. It contains important information that will help you to select the right type of wire for your work. It contains engineering information which illustrates why no one plastic compound is satisfactory for all wire and cable uses and lends weight to our statement that to get best results, plastic insulation, like rubber compounds, must be designed for the job in hand.

A copy of this Data Sheet will gladly be sent without obligation. Write for your copy of Data Sheet #114 today.

SIMPLEX WIRES & CABLES

SIMPLEX WIRE & CABLE CO.,
79 SIDNEY ST., CAMBRIDGE 39, MASS.

LABORATORY INSTRUMENTS FOR SPEED AND ACCURACY

BASIC EQUIPMENT FOR AUDIO MEASUREMENTS

RESISTANCE TUNED OSCILLATORS
Available in 7 models; frequency ranges between 2 cps and 200 kc. No zero setting. Constant output. Low distortion.

VACUUM TUBE VOLTMETER (MODEL 400A)
Full-scale sensitivity from .03 volts to 300 volts in 9 ranges. Input impedance 1 megohm in parallel with 16 mmf. Frequency response—10 cps to 1 mc.

AUDIO SIGNAL GENERATOR (MODEL 205AG)
Frequency range 20 cps to 20 kc. 5 watts output with less than 1% distortion. Output impedances of 50, 200, 500, and 5000 ohms, center-tapped. Output attenuator provides 110 db attenuation in 1 db steps.

Wherever audio-frequency and supersonic measurements are made, whether in an electronics laboratory, a broadcast station, or on a production line, -*hp*- equipment will speed the job and guarantee the accuracy of the results. Measurements of frequency response, gain, power, and voltage level throughout the audio-frequency and supersonic range can be made with -*hp*- Resistance Tuned Oscillators, Audio Signal Generators, and Vacuum Tube Voltmeters. Total distortion, hum, and noise are conveniently measured with -*hp*- Distortion Analyzers, and individual components of complex waves may be studied with the -*hp*- Model 300A Wave Analyzer. Frequency measurements are readily made with the Model 100B Secondary Frequency Standard or the Model 500A Electronic Frequency Meter. For more data on -*hp*- measurement equipment, write direct to factory.

HARMONIC ANALYZER (MODEL 300A)
Measures individual components of a complex wave. Frequency range 30 cps to 16 kc. Variable selectivity. Full-scale sensitivity from 1 millivolt to 300 volts.

HEWLETT-PACKARD COMPANY

BOX 1222 B • STATION A • PALO ALTO, CALIFORNIA

Audio Frequency Oscillators *Signal Generators* *Vacuum Tube Voltmeters*
Noise and Distortion Analyzers *Wave Analyzers* *Frequency Meters*
Square Wave Generators *Frequency Standards* *Attenuators* *Electronic Tachometers*

DOW CORNING
SILICONES

SILASTIC
FLUIDS
VARNISHES
RESINS
GREASES

withstand heat
resist oxidation
exclude moisture

SILASTIC* GASKETS

for the
most powerful aircraft
engine ever built!

chosen best among all gasket materials tested for service at 450°F.

Silastic gaskets fabricated from Dow Corning silicone rubber by the Connecticut Hard Rubber Co. seal 56 rocker boxes of the 28-cylinder Pratt & Whitney Wasp Major.

"NOTHING BUT THE BEST!" That's the policy followed by Pratt & Whitney in selecting materials for the powerful new 28-cylinder, 3650 h.p. Wasp Major.

That's why Silastic was chosen for these rocker box gaskets. Factors in the choice were Silastic's resiliency at the 450°F. operating temperature, resistance to the hot oil, and convenience in handling.

Silastic will fly with the Wasp Major in such giant new airliners as the Boeing Stratocruiser, Douglas Globemaster, Martin Mars, and Republic Rainbow.

If you need a rubber-like material that's resilient up to 500°F. and flexible down to −70°F., call for "Silastic Facts" No. 1A—and *TRY SILASTIC!*

*Trade Mark, Dow Corning Corporation

DOW CORNING CORPORATION · MIDLAND, MICHIGAN

Chicago Office: Builders' Building Cleveland Office: Terminal Tower
New York Office: Empire State Building
In Canada: Dow Corning Products Distributed by Fiberglas Canada, Ltd., Toronto

Dow Corning
FIRST IN SILICONES

OVER A THOUSAND DIFFERENT

STOCK Rheostats, Resistors, Tap Switches

AT

OHMITE

Offers a Quick Answer to Resistance Control Needs

Send for Stock-Unit Catalog No. 18

Write for this quick, helpful reference. Gives valuable data and information on the wide variety of Ohmite Stock Units

THE Ohmite stock of power rheostats, resistors and tap switches is the largest and most complete in existence . . . in variety and number!

Stock model rheostats are available in six different sizes from 25 to 500 watts . . . each size carried in more than a score of different resistance values . . . some as low as 0.5 ohm and others as high as 10,000 ohms.

Among the stock resistors are eight sizes of wire-wound fixed resistors rated at 1, 10, 20, 25, 50, 100, 160 and 200 watts. Also seven sizes of "Dividohm" adjustable resistors rated at 10, 25, 50, 75, 100, 160 and 200 watts. All sizes are available in scores of resistance values, some less than 1 ohm, others as high as 250,000 ohms.

There are also three series of stock tapped resistors (ten-section "Multivolts"), three series of non-inductive resistors, two series of glass-enclosed non-inductive resistors, five series of "Riteohm" precision resistors, seven series of tap switches, nine series of radio frequency chokes, and many other units.

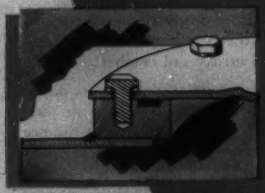
So great is the variety of Ohmite stock units that a combination of them can be used to obtain an endless number of resistances and wattage capacities. Special units engineered and produced to your specifications.

OHMITE MANUFACTURING COMPANY
4893 FLOURNOY STREET, CHICAGO 44, U.S.A.

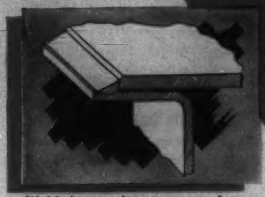
Be Right with **OHMITE**

RHEOSTATS • RESISTORS • TAP SWITCHES

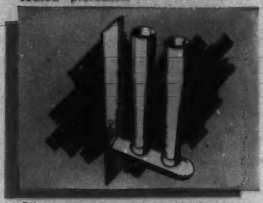
Maintenance Savings Begin with Design of the *tank* of a G-E TRANSFORMER



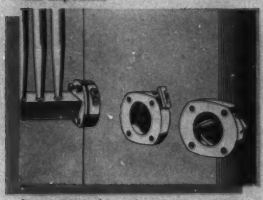
Synthetic rubber gasket plus metal-to-metal bolting gives weatherproof, liquid-tight joint on transformers rated above 2000 kva.



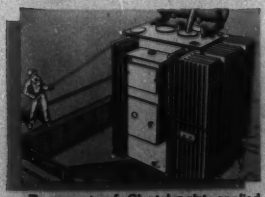
Welded cover for power transformers of 501 to 2000 kva provides "factory-sealed" protection.



Tubes are swaged at ends for extra thickness and strength at point of welds. This also gives more room for cleaning and inspection.



Larger tanks have detachable radiators. Radiator valves permit removal without draining the tank.



Three coats of Glyptal paint, applied on a clean, smooth, shot-blasted surface offer maximum resistance to weather.

In a G-E power transformer tank there is no such thing as a "minor detail." From the laboratory controlled selection of open-hearth steel plate, down to the 3 baked-on coatings of Glyptal paint, these tanks are built to give utmost protection to core and coils—*with a minimum of inspection and maintenance.*

Efficient protection of the insulating liquid from leakage, moisture absorption and oxidation is essential to trouble-free service. In the manufacture and design of G-E tanks, no effort is spared to provide oil tightness and moisture-proof construction. At the same time, all precautions are taken to assure that the unit will retain these maintenance-reducing qualities through many years of service under all weather conditions. Advanced welding methods, pressure-

Cover can be taken off and core and coils removed without completely draining tank.

Radiators are fabricated and thoroughly tested prior to their installation on the transformer tank.

These G-E tank-construction features keep maintenance costs low

1. Conveniently located filter press connections and oil sampling valve enable easy testing and conditioning of oil.
2. Welds which hold liquid are made externally for accessibility.
3. Tubes are braced against vibration.
4. Glyptal paint, applied over clean, shot-blasted surface inhibits corrosion.
5. Tubes are sturdy, swaged at ends to increase thickness at point of welding, and to reduce strains.
6. Tank is open-hearth steel, checked for carbon content to insure good welding qualities.
7. Properly compressed synthetic rubber gaskets or non-porous welds seal all tank joints.
8. Tube and header construction contributes to oil tightness by radically reducing the number of openings in the tank wall.

The tank is an integral part of a G-E transformer. Strength, shape of housing, liquid tightness, resistance to weather have all been considered. The result is a tank that is durable; that requires only a minimum of maintenance throughout the life of the transformer.

ting of welds, the use of synthetic rubber gaskets, uniform w-painting—all are major factors in the construction of E tanks.

This detailed forethought in the design of the tank typifies design of every element of a G-E transformer. First-hand perience with field maintenance conditions, an outstanding wledge of electrical design, and testing with the most up-date facilities have anticipated every feature that will cut vice costs and keep your transformer in continuous, efficient eration.

f you are in the process of selecting a transformer, look these features that will result in tangible savings in instal-on and maintenance costs. For information call your nearest E representative, or write to *Apparatus Dept., General ctric Company, Schenectady 5, N. Y.*

POWER TRANSFORMERS

GENERAL ELECTRIC

Yes, or alike as two telephone handsets made by the same process. Yet, pins or handsets — no two could ever be made exactly alike. Dimensions, weight, performance — all vary every time due to variables in manufacture. How can these variables be *controlled*?

Back in 1924, Bell Laboratories' mathematicians and engineers teamed up to find out, forming the first group of quality-control specialists in history. They invented the now familiar Quality Control Chart, designed inspection tables for scientific sampling. They discovered that test data mathematically charted in the light of probability theory were talking a language that could be read for the benefit of all industry.

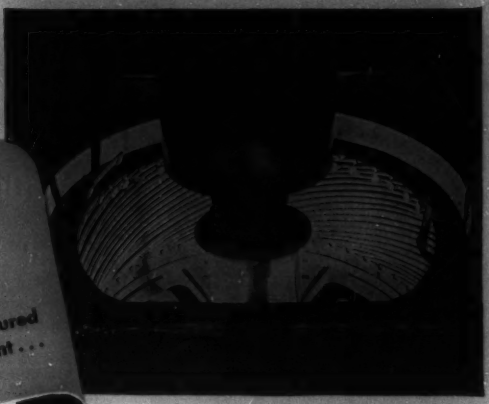
Western Electric, manufacturing branch of the Bell System, applied the new science to its large-scale production. In war, it was used by industrial and government agencies of the United Nations in establishing and maintaining standards for military matériel. A Quality Assurance Department, a novelty back in the nineteen-twenties, has come to be indispensable to almost every important manufacturer.

Scientific quality control is one of many Bell Laboratories' ideas that have born fruit in the Bell System. The application of mathematics to production helps good management all over the industrial world — and furthers the cause of good telephone service.

BELL TELEPHONE LABORATORIES

EXPLORING AND INVENTING, DEVISING AND PERFECTING FOR CONTINUED IMPROVEMENTS AND ECONOMIES IN TELEPHONE SERVICE.

In the Weather-Ometer, Weatherproof coverings are subjected to the accelerated aging effects of sunlight, wetting and drying, freezing and thawing, simulating rain, sleet and searing sun.



THE PAST...

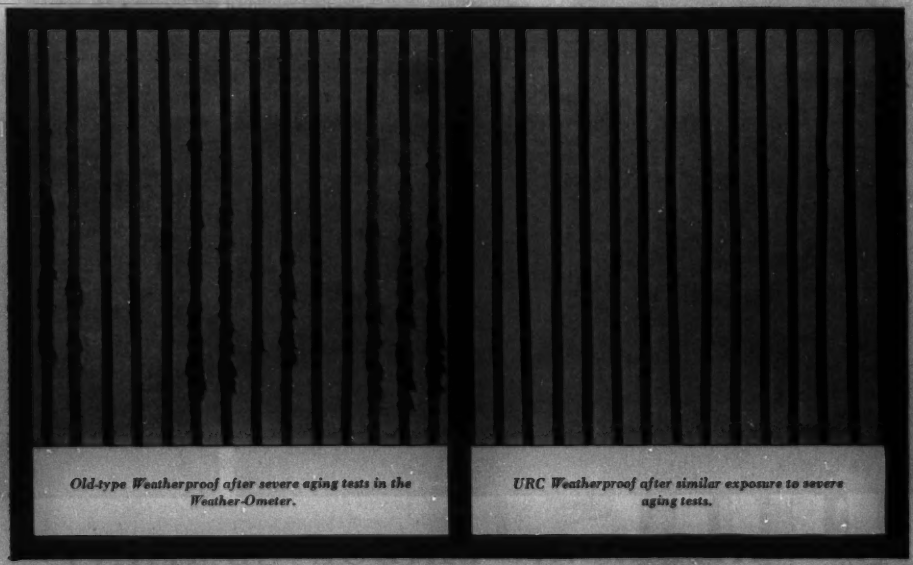
"Festooning" was not unusual...

THE PRESENT...

Today, lasting Weatherproof is assured by URC research and development...

For Continuity of Service... Anaconda Triple Braid or Duraline URC

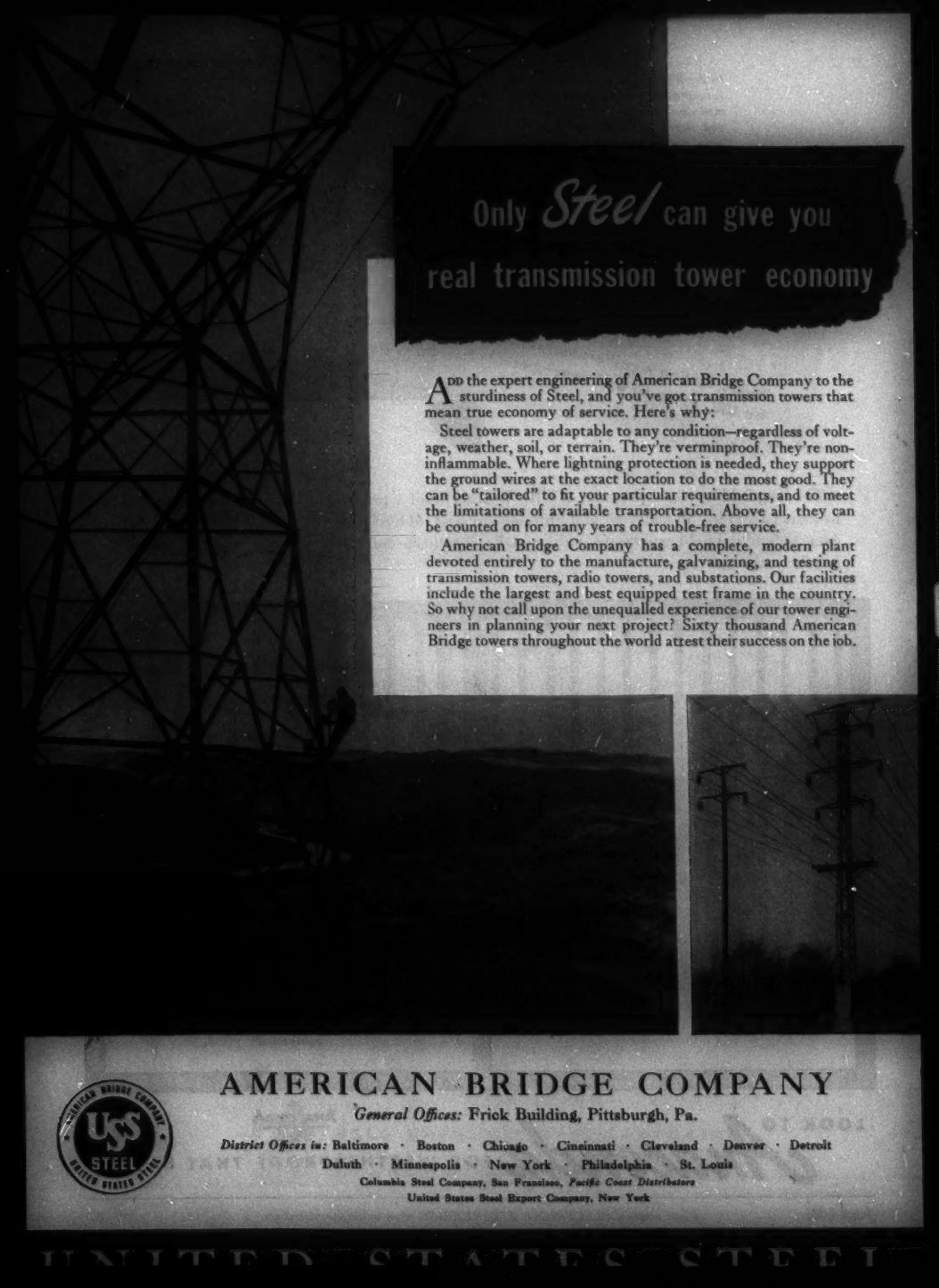
• **The long field service expectancy of URC Weatherproof is proven by exhaustive tests on materials and finished wire and cable. These data, plus actual field experience, indicate URC Weatherproof will last for years and years.**



Old-type Weatherproof after severe aging tests in the Weather-Ometer.

URC Weatherproof after similar exposure to severe aging tests.

LOOK TO *Anaconda* ANACONDA **FOR WEATHERPROOF THAT LASTS!**



Only *Steel* can give you real transmission tower economy

Add the expert engineering of American Bridge Company to the sturdiness of Steel, and you've got transmission towers that mean true economy of service. Here's why:

Steel towers are adaptable to any condition—regardless of voltage, weather, soil, or terrain. They're verminproof. They're noninflammable. Where lightning protection is needed, they support the ground wires at the exact location to do the most good. They can be "tailored" to fit your particular requirements, and to meet the limitations of available transportation. Above all, they can be counted on for many years of trouble-free service.

American Bridge Company has a complete, modern plant devoted entirely to the manufacture, galvanizing, and testing of transmission towers, radio towers, and substations. Our facilities include the largest and best equipped test frame in the country. So why not call upon the unequalled experience of our tower engineers in planning your next project? Sixty thousand American Bridge towers throughout the world attest their success on the job.

AMERICAN BRIDGE COMPANY

General Offices: Frick Building, Pittsburgh, Pa.

District Offices in: Baltimore · Boston · Chicago · Cincinnati · Cleveland · Denver · Detroit
Duluth · Minneapolis · New York · Philadelphia · St. Louis
Columbia Steel Company, San Francisco, *Pacific Coast Distributors*
United States Steel Export Company, New York

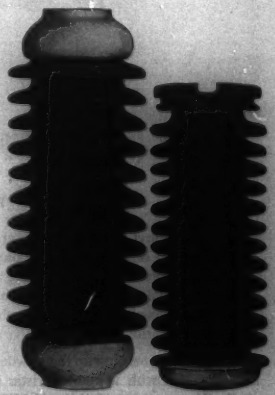
AMERICAN BRIDGE COMPANY · USS STEEL · UNITED STATES STEEL

UNITED STATES STEEL

LINE POST LINES
ARE PERMANENTLY RADIO-FREE
In the days when complaints of radio interference constituted the number-one headache to Customer Relations and Transmission Engineering departments, the Lapp Post series of insulators offered the first completely satisfying answer. Radio-free by design—corona cannot form at rated operating voltages and well beyond—Line Posts and Station Posts provide permanent and complete elimination of insulator-generated radio noise.
CUSTOMERS' COMPLAINTS DEPARTMENT
1930
1934
1935
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945

LAPP LINE POSTS HAVE A 15-YEAR SERVICE RECORD

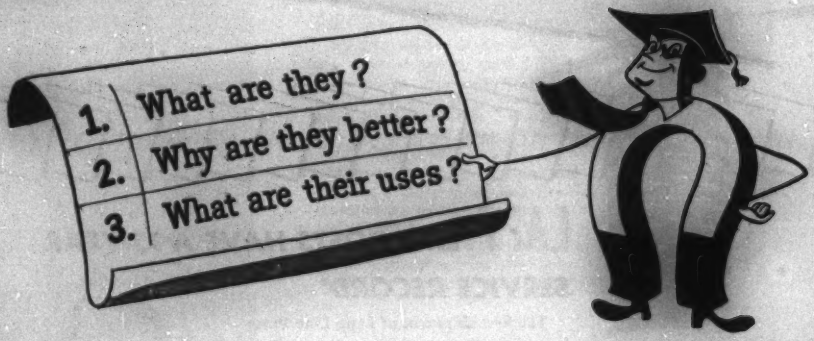
The first shipment of Lapp Line Posts went into service 15 years ago. The installation was the one which had inspired The Line Post design—a particularly bad, and previously unsolved, dirt condition. Since then, hundreds of thousands of Lapp Posts have gone up, in many cases a desperation answer to a difficult service problem—dirt condition, mechanical attack, radio noise, arcover failure. And the 15-year service record of these insulators shows them to stand up better, with fewer line outages, and lower replacement ratio, than any other insulator now in use.



Lapp

LAPP INSULATOR COMPANY, INC., LE ROY, N. Y.

The 3 "most-asked" questions about Carbonyl Iron Powders



For wartime uses, design engineers asked these three questions.

In peacetime, as design engineers plan for peacetime equipment, the same questions are asked.

"What are they?"

G.A.F. Carbonyl Iron Powders are obtained by thermal decomposition of iron penta-carbonyl. There are five different grades in production, designated as "L," "C," "E," "TH," and "SF" Powder. Each of these five types of iron powder is obtained by special processing methods and has its special field of application.

The particles making up the powders "E," "TH," and "SF" are spherical with a characteristic structure of concentric shells. The particles of "L" and "C" are made up of homogeneous spheres and agglomerates.

Their weight-average diameter, their total iron contents, and their carbon contents are given in the table at upper right.

"Why are they better?"

Carbonyl Iron Powders are better because of their unique spherical shape, shell structure, particle size distribution, high degree of purity and freedom from stress.

Their stability against magnetic shock, temperature changes, and time (aging) is of the highest order.

Permeabilities range up to 70 with low eddy-current losses. Q values are the highest obtainable because of extremely small eddy-current and hysteresis losses.

Carbonyl Iron Powders are better as electromagnetic material over the entire communication frequency spectrum.

A set of relative Q values for the five powder grades is given in the graph on the other page to show the conventional frequency range for each grade.

"What are their uses?"

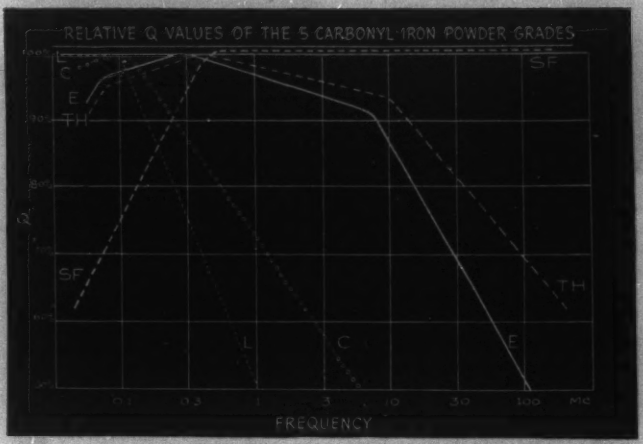
Carbonyl Iron Powders are used for electromagnetic cores and structures for widely different purposes. Five typical applications are shown on the chart at bottom of other page.

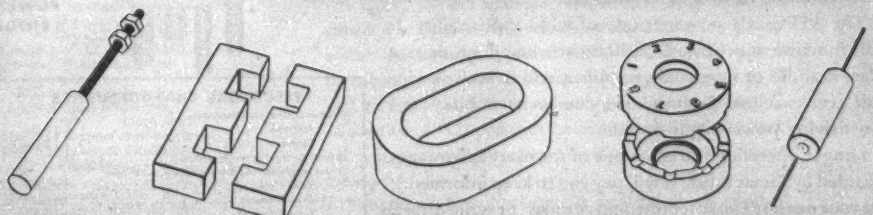
"L" and "C" powders are also used as powder metallurgical material because of their low sintering temperatures, high tensile strengths, and other very desirable qualities. Sintering begins below 500°C and tensile strengths reach 150,000 psi. Compacts can be made having regular pronounced porosity to function as a spongy mass. Compacts can also be made of highest density for excellent magnetic properties.

Further information can be obtained from the Special Products Sales Dept., General Aniline & Film Corporation, 270 Park Avenue, New York 17, N. Y.

Diameters and Chemical Composition of the 5 Carbonyl Iron Powder Grades

Carbonyl Iron Grade	Weight-Average Diameter Microns	Total Fe Content %	Total Carbon Content %
L	20	99.7-99.9	0.005-0.03
C	10	99.5-99.8	0.03 -0.12
E	8	97.9-98.3	0.65 -0.80
TH	5	98.1-98.5	0.5 -0.6
SF	3	98.0-98.3	0.5 -0.6





"L" Type Powder used in cores for permeability tuning.

"C" Type Powder for E-cores in filter coils.

For antenna coils, "E" Type Powder used in cores.

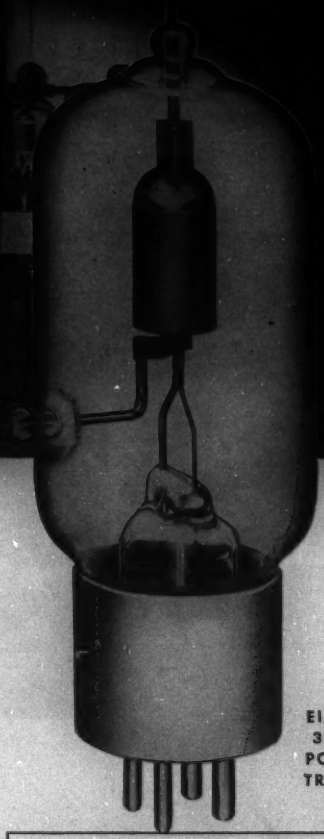
"TH" Type Powder is employed for cup shields in coils.

One use of "SF" Type Powder is in high frequency choke cores (with sealed-in leads).

G.A.F. CARBONYL IRON POWDERS

Eimac

THE COUNTERSIGN OF DEPENDABILITY IN ANY ELECTRONIC EQUIPMENT



EIMAC 35TG POWER TRIODE

A BETTER 35TG

The famous Eimac 35TG VHF tube, with its low interelectrode capacitances, its logical terminal arrangement, its lack of internal hardware, *is further improved.* It now has a non-emitting grid, an improved filament, and a cooler operating plate. These improved elements, the result of wartime developments in manufacturing technique, are being incorporated in many Eimac tubes and are consistently resulting in vastly increased life.

The 35TG is a power triode of wide applicability. It will function as a Class-C oscillator or amplifier, or as a Class-B audio or supersonic amplifier, and in such service will give excellent performance, due to its stability and low driving-power requirements.

Longer operating life is but one of the many advantages afforded by Eimac tubes. It will pay you to keep informed... see your nearest Eimac representative today, or write direct.

ELECTRICAL CHARACTERISTICS

Filament: Thoriated tungsten	
Voltage	5.0 volts
Current	4.0 amperes
Amplification Factor (Average)	39
Direct Interelectrode Capacitances (Average)	
Grid-Plate	1.8 uuf
Grid-Filament	2.5 uuf
Plate-Filament	0.4 uuf
Transconductance (I_b = 100 ma., E_b = 2000 V., E_c = −30 V.)	2850 umhos
Frequency for Maximum Ratings	100 mc

Follow the leaders to

Eimac TUBES

EITEL-McCULLOUGH, INC.
1229 R San Mateo Ave., San Bruno, Calif.
Plant located at: San Bruno, California

Export Agents: Frazar and Hansen, 301 Clay Street, San Francisco 11, California, U. S. A.

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ROYAL J. HIGGINS (W9AIO), 600 S. Michigan Ave., Room 818, Chicago 5, Illinois. Phone: Harrison 5948.

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THE NEW Fibron #5373

FLEXIBLE PLASTIC TUBING

Test Data

Tensile Strength	3000 P.S.I.
Dielectric Strength (.020" wall) Wet	1000 VPM
Dry	1000 VPM
Life at 105° C.	2000 Hrs.
Chemical Resistance (room temperature)	
50% Sulfuric Acid and 30% Sodium Hydroxide	Unaffected
Does not support combustion	
Low Temperature Flexibility	
I.V.I. Pinch test	—40°C.
Bell test	—30°C.
Heat Endurance (.166" ID tubing, .016" wall) ASTM-D350-43T): 7 days @ 125°C.—No crack when bent 180° around ¼" mandrel—Retains flexibility when varnished and baked 22 hours at 260°F.—No flow or drip during 8 hours at 300°F.	

This Irvington formulation provides new advantages, new cost-saving features, for many plastic tubing applications. For example: Transformer leads of #5373 remain flexible even after varnishing and baking . . . Underwriters' Laboratories approved #5373 insulation on applications involving continuous operating temperatures up to 75 deg. C. and intermittent temperatures as high as 85 deg. C. In addition, #5373 possesses the excellent electrical, mechanical and chemical properties which distinguish all Fibron tubings.

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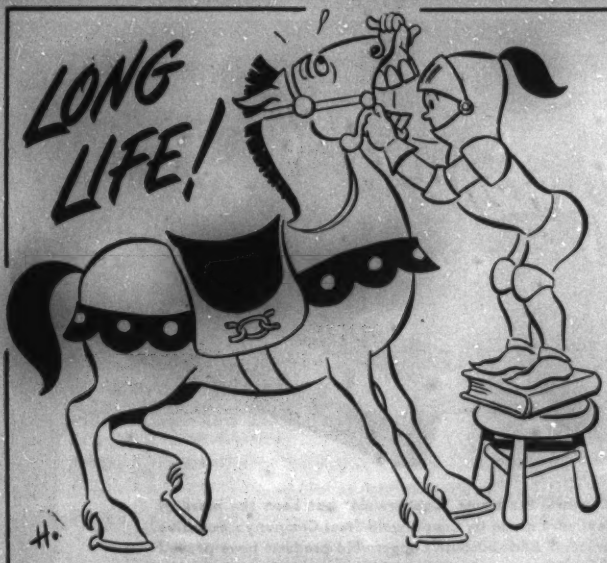

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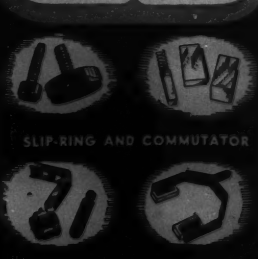

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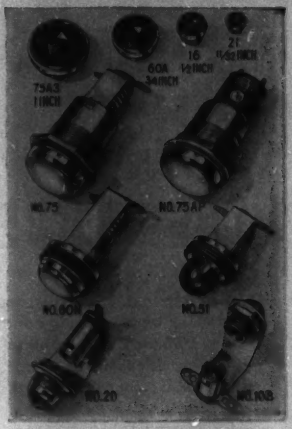

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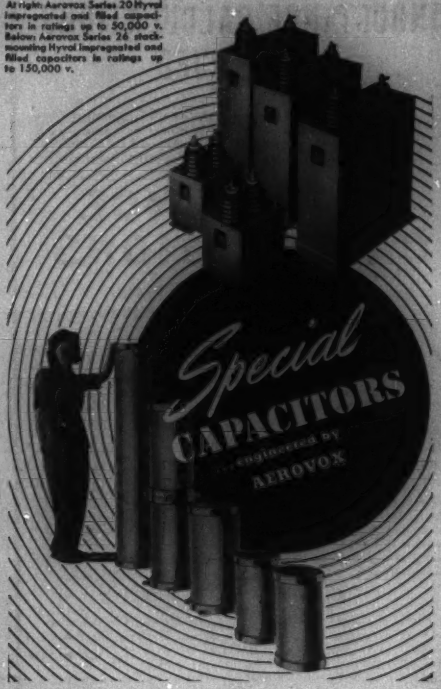

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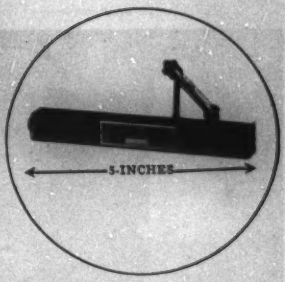

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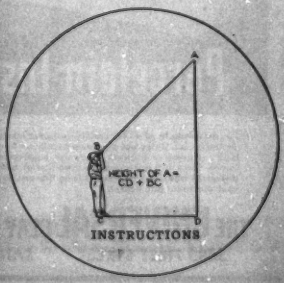

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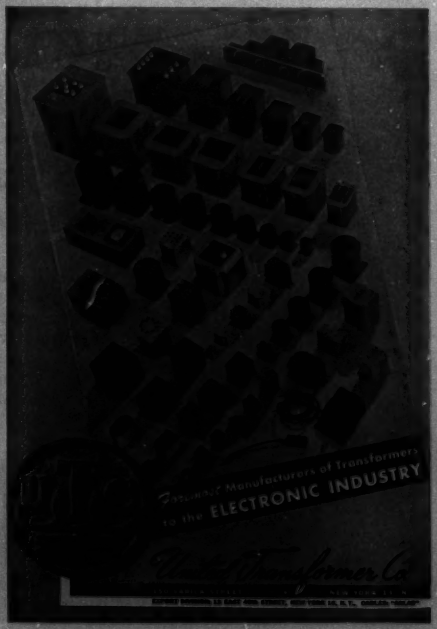

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ERRATA—Standard 45, Pages 30 and 31
Sections 18.65, 67, 69, 81, 83 and 88
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EXECUTIVE ENGINEERS, 2, 35–45, electrical or mechanical graduates of recognized colleges with at least five years' experience in industry in executive capacity. Will be responsible for efficient, business-like operations of a medium sized engineering department, completely staffed technically. Salaries, $7500–$8000 a year. Locations: one for truck assembly plant in south central New York; this applicant must have had extensive experience in truck engineering design; the other for communications equipment plant in Connecticut. W-6958.

PRODUCT ENGINEERS, electrical, mechanical or chemical graduates, preferably with two years' experience in product engineering work, for work on technical glass products, including choice of glass composition, design to meet customers requirements, supervising manufacturing drawings and specifications. Salary, $3000–$4500 a year. Location, upstate New York. W-7065.

ELECTRICAL ENGINEERS with training and experience in electronics. Salary, $3330–$5180 a year. Location, Virginia. W-7078.

ENGINEERS. (a) Development Engineer, electrical graduate, with at least ten years' experience in research and development of radio and telephone communication equipment, to assist in circuit development program. (b) Model Makers, junior and senior, with four to five years' radio experience, to produce test items from sketches and verbal instructions. Salaries: (a) $4800–$6000; (b) $3300 a year. Location, New York, N. Y. W-7125.

ENGINEERS. (a) Engineer experienced in electrical wiring materials and prices gained through years of contact with electrical wholesalers of such materials. Must know prices. (b) Electrical Engineer familiar with local utility engineering practices and having had some sales experience. Must have, or obtain, New York State Professional License. (c) Electrical Engineer, graduate, to learn electrical construction designing. Location, New York, N. Y. W-7140.

ENGINEERS, to 45, electrical graduates or equivalent. (a) Development Engineer with experience in the design and development of telephone and signalling equipment and components. Salary, $4420 a year. (b) Product Designer with experience in mechanical design pertaining to electro-mechanical devices. Thorough knowledge of mechanical motions, gearing, etc., essential. Salary, $3900 a year. Location, Connecticut. W-7130.

INSTRUCTORS of electrical engineering. (a) Assistant Professor with some teaching experience. (b) Instructor with or without experience, but with an interest in teaching. Salaries open. Location, Massachusetts. W-7138.

INSTRUCTOR to teach electrical measurements laboratory, service courses based on such texts as Blalock and Fitzgerald, and a major course at sophomore level based on Timbie and Bush with emphasis on problem material. Salary, $2000–$2500. Position starts September 1946. Location, Maine. W-7199.

INSTRUCTORS AND ASSISTANT PROFESSORS of electrical engineering, engineering mechanics or engineering drawing. Bachelor's degree required for Instructor; Master's for Assistant Professor. One year of teaching required for Instructor and five or more for Assistant Professor. Appointments for fall term of 1946. Salaries approximately $2300–$3500. Location, Michigan. W-7215-D-2868.

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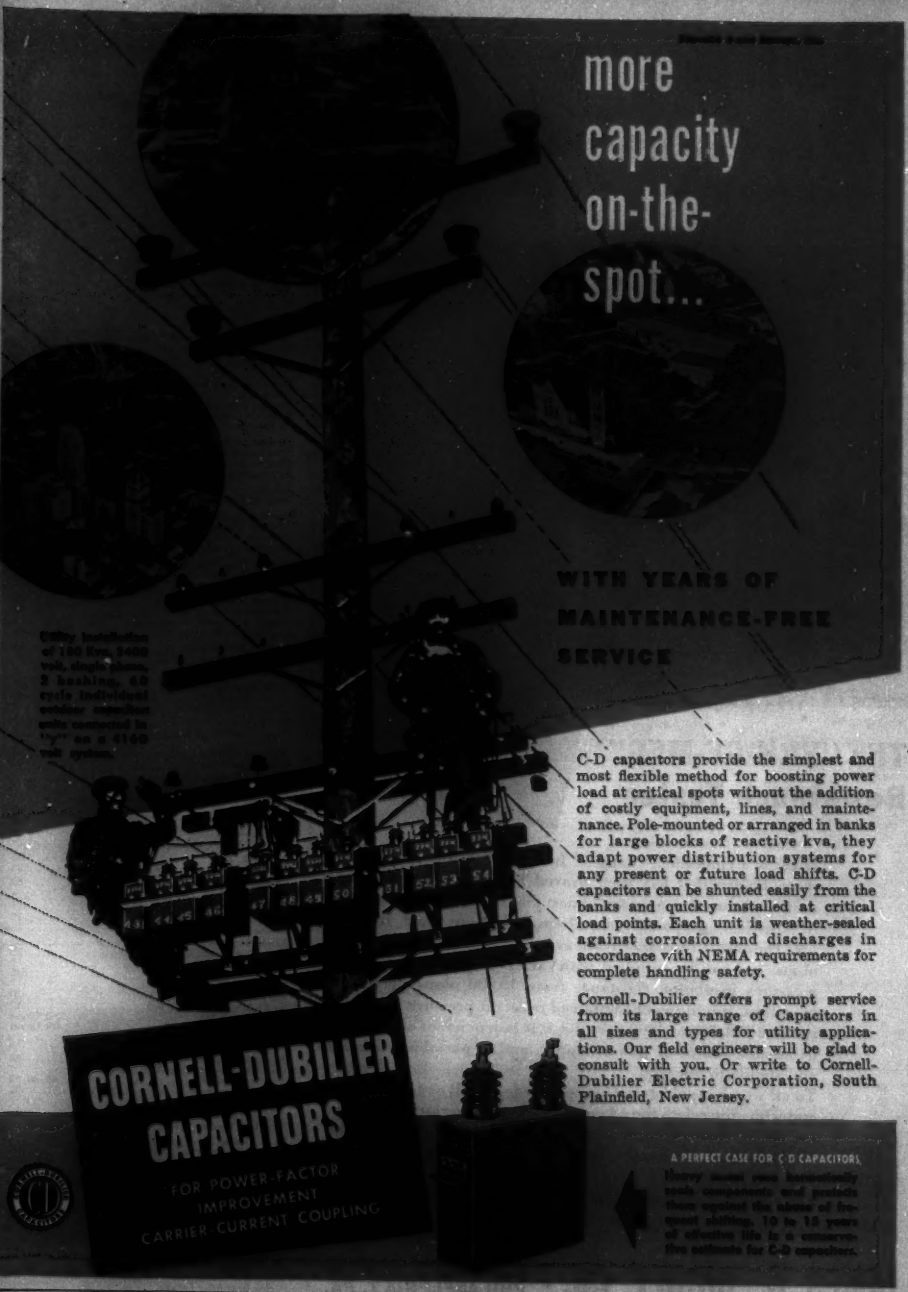

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ADVERTISERS

	Page
Acme Electric Co.	45
Ascovox Corp.	50
Allis-Chalmers Mfg. Co.	*
Aluminum Company of America	6
American Bridge Co.	36
American Lava Corp.	8
American Steel & Wire Co.	*
American Transformer Co.	14
Amperite Co.	50
Anaconda Copper Mining Co.	37
Arnold Engineering Co.	49
Baldwin Mfg. Co.	*
Bell Telephone Laboratories	39
Bethlehem Steel Co., Inc.	*
Biddle Co., James G.	56
Black & Veatch	53
Brown, Christian K.	53
Brush Development Co.	4
Burndy Engineering Co.	15
Chicago Transformer Co.	51
Classified Advertisements	54
Concord Radio Corp.	54
Coors Porcelain Co.	52
Copperweld Steel Co.	45
Cornell-Dubilier Electric Corp.	55
Corning Glass Works	*
Davis, Julien H.	53
Delph Co., John C.	*
Dow-Corning Corp.	32
Drake Mfg. Co.	48
Dumont Laboratories, Allen B.	25
Dana Co., Struthers	*
du Pont de Nemours & Co., E. I.	13
Ebtel McCullough, Inc.	42
Electrical Reactance Corp.	*
Electric Service Control Co.	46
Engineering Soc. Personnel Service	54
Federal Tel. & Radio Corp.	47
Ferranti Electric, Inc.	19
General Aniline & Film Corp.	40, 41
General Electric Co.	7, 12, 34, 35
General Radio Co.	16
Graphite Metallizing Corp.	48
Harvey Wells Electronics Inc.	*
Hewlett-Packard Co.	31
Hodgson & Associates	53
Indiana Steel Products Co.	21
International Resistance Co.	24
Irvington Varnish & Insulation Co.	43
I-T-E Circuit Breaker Co.	3rd Cover
Jackson & Moreland	53
Johns-Manville Co., H. W.	28
Karlte Company, The	9
Lapp Insulator Co.	39
Lederman, Frank	53
Leeds & Northrup Co.	2
Matthews Corp., W. N.	51
Measurements Corp.	*
Miner & Miner	53
Moloney Electric Co.	27
Morganite Brush Co.	46
National Carbon Co.	*
National Electric Coil Co.	*
National Varnished Products Corp.	*
Ohio Brass Co.	29
Ohmite Mfg. Co.	53
Okonite Company, The	5
Owens-Corning Fiberglas Corp.	*
Polachek, Z. H.	53
Professional Engineering Directory	53
Quinn Co., George E.	53
Radio Corporation of America	*
Raytheon Mfg. Co.	*
Rockbestos Products Corp.	10
Rowan Controller Co., The	26
Sanderson & Porter	53
Sargent & Lundy	53
Schweitzer & Conrad, Inc.	*
Selenium Corp.	46
Shallcross Mfg. Co.	*
Simplex Wire & Cable Co.	30
Smith Mfg. Co., F. A., Inc.	17
Sola Electric Co.	2nd Cover
Solar Mfg. Co.	4th Cover
Sprague Electric Co.	*
Square D Company	*
Stackpole Carbon Co.	22
Standard Electric Time Co.	*
Standards—AIEE	44, 48, 53
Stampf, George E.	53
Superior Electric Co.	*
Triplett Electrical Instrument Co.	44
Trumbull Electric Mfg. Co.	18
U. S. Rubber Co.	11
U. S. Steel Corp.	38
United Transformer Co.	52
Universal Clay Products Co.	52
D. Van Nostrand Co., Inc.	49
Waldes-Kohinoor Inc.	23
War Assets Administration	20
Westcott & Mapes, Inc.	53
Westinghouse Electric Corp.	*
Weston Electrical Instrument Corp.	*
White, J. G., Engineering Corp.	53
Wiley, John & Sons	*
Wray, I. G.	53

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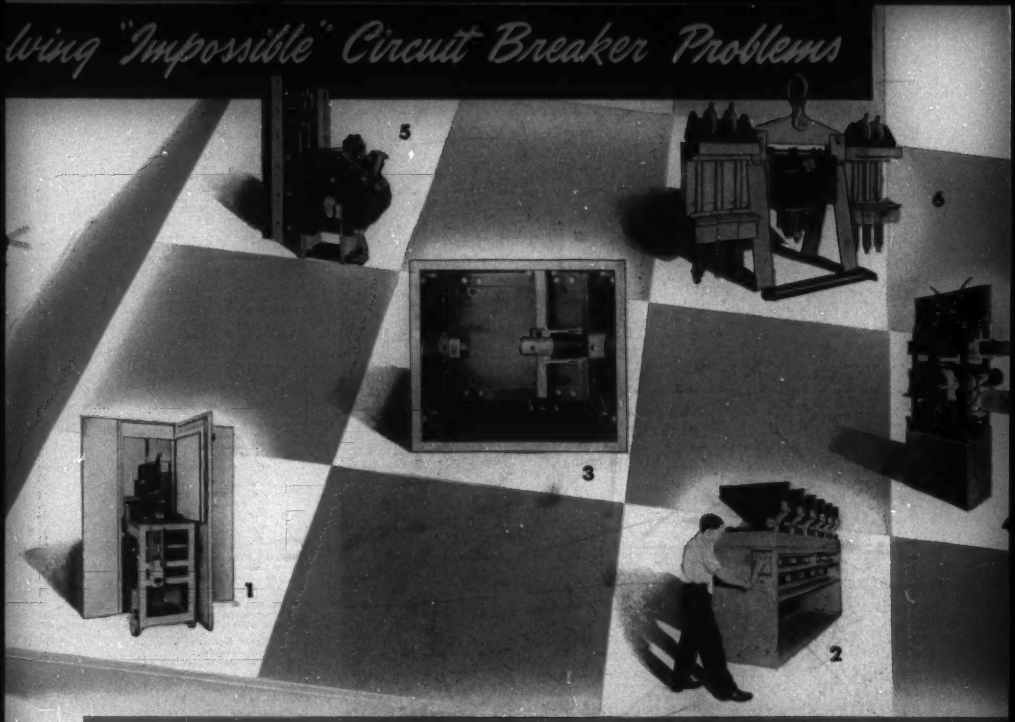

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AMBIENT TEMPERATURE: 65°C

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